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Development, sugar yield, and ethanol potential of sweet sorghum

Emily Lucille Hunter
Iowa State University

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Emily Lucille Hunter

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INTRODUCTION

With the advent of several energy crises, energy production from crops has gained sporadic attention in the USA. This interest has recently been rekindled due to the requirements of the Clean Air Act and an increased public interest in environmental quality. The USDA Biofuels Initiative instigated a research program for substantiating the economic viability of biofuels production (Conway et al., 1992). These efforts are in part to reduce the dependency of the USA on imported oil and to decrease this addition to the U.S. deficit through an increase in renewable fuel production and consumption. In 1993, renewable energy technologies accounted for almost ten percent of the nation's energy production, which is more than double their contribution since 1973 (Sklar et al., 1993).

More attention has been paid to energy production systems based on a closed carbon cycle. Unlike fossil fuels, in the combustion of biofuels the carbon released is converted to phytomass within the same period of time as its release. Major advances have yet to be made in increasing the conversion economics, in utilizing coproducts, and in cellulosic feedstock conversion (Witman and Evans, 1992) to improve our use of the closed energy cycle. In making such advances, rural economies could be affected in several ways: energy crop production could be incorporated into whole-farm plans, local feedstock production and processing could increase employment opportunities, and government subsidies could be decreased.

Biomass provided over 3.5 quads, or 22 % of the annual imported oil consumption, of the energy used in the USA in 1991. Of that, 3.8 billion L of ethanol was used in transportation fuels, up from 76 million L in 1979 (Harris and Rosen, 1992). In 1991 10.2 million Mg of corn were utilized in ethanol production; 3.4 million of those Mg originated in Iowa (Iowa Corn Promotion Board, 1991). Over 95 % of the fuel ethanol produced in U.S. is made from maize (*Zea mays* L.). Seven % of gas consumed in the U.S. is an ethanol blend. It is projected that over 9.1 billion L will be consumed annually by the year 2000 (Harris and Rosen, 1992). The cost of biofuels in general is expected to be down to approximately $0.18 per L by the year 2000 (Sklar et al., 1993). Currently, the strongest market for ethanol is the midwest (Harris and Rosen, 1992).

Although the use of ethanol was not uncommon at the turn of the century, ethanol's value was first recognized as an octane booster or gas extender in the 1970's. Later the value of the 10 % blended fuels was seen as an oxygenate, useful in reducing carbon monoxide emissions (Lee and Conway, 1992). Now it is also a feedstock for the ethanol based ether, ethyl tertiary butyl ether (ETBE). In the future its value will increase as an alternative fuel.

Potential feedstocks for a new crop-based energy production system range from starchy and sugary tuberous crops (Hinz et al., 1985), to woody crops (McClelland and Farrell, 1992), to oilseed crops, to a host of herbaceous crops. Herbaceous energy crops include row crops such as maize, sweet and grain sorghums (*Sorghum bicolor* [L.] Moench; Parish et al., 1985), temperate grasses such as reed canarygrass (*Phalaris arundinacea* L.) and warm season grasses such as switchgrass (*Panicum virgatum* L.; McClelland and Farrell, 1992), and the production of tropical gasses in temperate regions (Woodard and Prine, 1993). Recently, the search has emphasized non-food crops.

An important characteristic of biomass crops is a high crop product energy to crop cultural energy ratio (Putnam et al., 1991). The most costly input in the cultural energy component is nitrogen fertilizer. Thus, the evaluation of potential energy crops must emphasize N inputs; its efficient use is critical. Due to its low crop product energy to crop cultural energy ratio, it is not probable that maize-based ethanol will meet all future liquid fuel demands (McClelland and Farrell, 1992). As an energy source, it is also limited by the inefficiency of converting starch to ethanol and by conservation considerations such as suitable land use. Furthermore, ethanol from alternative crops will increase farm diversity and sustainability (Keeney and DeLuca, 1992).

Sweet sorghum is an example of a crop that is biologically competitive with maize and has a more beneficial energy balance. This has been borne out in fertility studies where N rates greater than 56 kg ha^{-1} show no effect on yield (Lueschen et al., 1991). Dry matter yields may be increased, but total sugar yields, and in turn ethanol yields, are not. This result was attributed to residual soil N and to the space-compensating growth patterns of sorghum (Lueschen et al., 1991). Based on comparable, theoretical ethanol yields (converted soluble carbohydrates), 190, 140, and approximately 90 kg N ha^{-1} are required for corn, grain sorghum and sweet sorghum production respectively (Wiedenfeld, 1984).

The efficient use of resources in the acquisition of carbon for storage carbohydrates increases the economic potential of sweet sorghum. Sweet sorghum is one of the world's most photosynthetically efficient crops. It has enormous growth rates and can reach heights of 3 to 5 m (Miller and McBee, 1993). Acceptable yields have been obtained at locations across the continental U.S. (Smith et al., 1987, Hills et al., 1990, Lueschen et al., 1991). A differential of 120 to 300 frost-free days was shown to account for an average 67 % increase in potential ethanol production (Smith et al., 1987). Cultivars adapted to the gulf coast states have been particularly productive in the midwest. Yields of fermentable carbohydrate range from 2.3 to 6.8 Mg ha^{-1} (Smith and Buxton, 1993, Putnam et al., 1991). A study comparing ethanol production from six energy crops showed that sugarbeet (*Beta vulgaris* L.) and sweet sorghum may be superior to maize in production of fermentables over a wide range of environments (Parrish et al., 1985).

There is a wealth of genetic variation in the *S. bicolor* races (deWet and Harlan, 1971). Manipulation of these differences has resulted in highly divergent resources, from many-culmed, leafy forages to compact, productive grain hybrids. In the history of sweet sorghum improvement in the USA, the emphasis has been on multiple purposes-sugar production, syrup production and use as a forage. In the collection activities around the world, a wide genetic base has been preserved in sweet sorghum germplasm. The emphasis of this preservation has been on disease resistance and adaptability. More specifically, the sweet sorghum cultivars have proven exceptionally adaptive to a wide range of environments for a grass of tropical origin (Smith et al., 1987). Therefore, in the search for energy crops, sweet sorghum is a strong candidate.

The objectives of this study were to evaluate the productivity of a group of sweet sorghum cultivars of varying maturity and morphology, to determine the patterns of sugar accumulation in the cultivars over the field season, to examine growth patterns in the cultivars, and finally to evaluate sweet sorghum as an energy crop by producing ethanol from the cultivars processed as silage.

LITERATURE REVIEW

Sorghum Bicolor ssp. Bicolor

Sorghum bicolor belongs to the Poaceae tribe, Andropogoneae. The tribe includes many of the tall grass genera characterized by the C4 photosynthetic pathway and high productivity. Some of these include: Miscanthus, Andropogon, Tripsacum, as well as Zea and Saccharum. Sweet and grain sorghum share the same genus and species. The cultivated races are in the subspecies bicolor whereas the spontaneous races belong to the subspecies arundinaceum (Harlan and deWet, 1972). Five fairly distinct races, ten intermediate cultivated races, and six spontaneous races are all included in the *bicolor* species. Most sweet-stalked cultivars originated from the bicolor race or its intermediates.

The bicolor race exhibits the most morphological variation of the five races, yet is presently least cultivated in general (Harlan, 1975). The bicolor race is typified by long, hard, clasping glumes, an elongate seed shape, long stiff awns, and an open inflorescence. These characteristics are usually associated with primitive cultivars (Harlan and deWet, 1972). This race has several subraces. The sorgo subrace contains most of the sweet stalked types (Harlan and deWet, 1972). Traits from other races have been incorporated in sweet sorghum cultivars to improve characteristics such as seed size for harvestability. Also, introgression of wild types and old cultivars for improving resistances has introduced new inflorescence characteristics and general morphologies. Therefore, sweet sorghum cultivars display a wide variety of seed types and panicle shapes.

Major advances in sorghum breeding were made in a conversion project by Stephens et al. (1967). Using a vast array of germplasm, many short, early sorghums were produced that have been especially productive in the temperate zone. The vulnerability of sorghum cultivars to diseases and pathogens was reduced as a result of this use of a wide germplasm base. In the sorghums, there is a positive correlation between plant height and yield. In turn, plant height and maturity are positively correlated traits (Miller and McBee, 1993). By planting late-maturing sweet sorghum cultivars in areas with long daylengths, this maturity by yield relationship is manipulated by intentional photoperiod regulation. Thus, in addition to plant breeding, management practices are used to maximize yields (Miller and McBee, 1993).

High energy sweet sorghum types have been developed which are sweet-stalked yet have relatively high grain yields. These hybrids utilize a grain type female and a sweet type male. The product is taller than the female and has increased stalk sugar concentrations (Miller and McBee, 1993). When male parents have inherently high non-structural carbohydrate levels, the hybrid progidy will most likely also have high non-structural carbohydrate concentrations. Female parents may also enhance sugar production. From a breeding perspective, manipulation of soluble carbohydrates in the stalk and their proportion of the total stalk biomass is important (Miller and McBee, 1993). Advances could also be made in decreasing lodging, manipulation of maturity genes, and the production of male sterile cultivars to increase the stalk carbohydrate levels in sweet sorghum.

Sweet Sorghum Growth Characteristics

In a study comparing growth of sweet and forage sorghum, Ferarris and Charles-Edwards (1986a) found that each cultivar exhibited a "space-saving" plasticity. Plants grown at lower densities compensated by producing more and heavier culms by maturity. This resulted in a higher efficiency of solar radiation use during the maturation period. A forage sorghum might be expected to produce more leaf mass than a sweet sorghum cultivar, due to selection for grazing (i.e., more tillers and branches). However, leaf area for the sweet sorghum cultivar was greater before anthesis. At anthesis, the forage sorghum produced more tillers and ultimately the cultivars partitioned similar amounts of above ground dry matter to leaf tissue (Ferarris and Charles-Edwards, 1986a). The stems and leaves of sweet sorghum are considered non-senescent; they are photsynthetically active after the grain is mature (Nan and Ma, 1989).

Grain sorghum cultivars are more similar to sweet sorghum in morphology and leaf architecture than to the forage types. Vietor and Miller (1990) found that leaf area in a sweet sorghum cultivar was twice that of a grain hybrid. Even when the sweet sorghum cultivar was defoliated to minimize the differences in leaf area, it accumulated twice as much nonstructural carbohydrate in upper branches (Vietor and Miller, 1990). Starch levels increased similarly in both types of cultivars until anthesis (McBee and Miller, 1982), and total nonstructural carbohydrates were similar at the preboot stage (Vietor and Miller, 1990). After anthesis and throughout the maturation period, however, concentrations of nonstructural carbohydrates were approximately two times greater in the sweet sorghum representatives (Vietor and Miller, 1990). McBee et al. (1983) suggest that after anthesis assimilate production in sweet sorghum is in excess of the sink demand of the panicle and the levels of nonstructural carbohydrate accumulate in the upper stems. In the forage and sweet sorghum comparison, distribution of sugars was similar before anthesis, but, when mature, the sugar concentration in the sweet sorghum cultivar was ten times higher than that of the forage sorghum (Ferarris and Charles-Edwards, 1986b).

In comparing a sweet sorghum hybrid with a grain sorghum hybrid, the carbon exchange rate (CER) of the upper and lower leaves declined two and three times more rapidly, respectively, in the grain sorghum (Vietor and Miller, 1990). The higher CER of the sweet hybrid was associated with greater amounts of nonstructural carbohydrate after maturity; a higher, non-senescing leaf area indicated a non-limited source (Vietor and Miller, 1990). Carbon assimilation rates and stomatal conductance were measured in several grain sorghum cultivars (Kidambi et al., 1990). When assimilation rates were regressed on conductance, the two were highly correlated. The slopes differed by species and by environment, indicating differences in intrinsic gas exchange efficiency.

Wiedenfeld (1984) found that N uptake in sweet sorghum did not increase when levels of available N were increased from 112 kg N ha^{-1} to 224 kg N ha^{-1} and that uptake efficiency decreased by one half. In comparing N use by forage sorghum with sweet sorghum, differences were noted in partitioning patterns due to morphology (Ferarris and Charles-Edwards, 1986b). Genotypic differences in remobilization of N from different plant tissues were also observed. However, there was little difference between cultivars in N concentration and its logarithmic decrease over time (Ferarris and Charles-Edwards, 1986b). The differences arise in the amount of carbon gained per unit N taken up, especially in early growth stages. Extremely high rates of N application affected the distribution of N in the above ground plant tissues and decreased the total dissolved solids in the juice of the sweet sorghum cultivars (Wiedenfeld, 1984).

Given the continued interest in drought tolerant crops, water-use efficiency in grain sorghum has been well-characterized (e.g., Bremner and Preston, 1990, Kidambi et al., 1990, and Hattendorf et al., 1988). In a study comparing a grain sorghum and a sunflower hybrid, both characterized by high water-use efficiencies, sorghum exhibited a 75 % grain yield increase after a long period of drought-induced arrested development was broken by watering (Bremner and Preston, 1990). In the southeastern USA, interest in sweet sorghum as an interim crop in sugarcane (*Saccharum officinarum* L.) and vegetable production systems has increased. Water management is also an issue in this region. Shih (1986) showed that the water-use efficiency of sweet sorghum was inversely related to water table depth. A whole plant simulation model was designed to investigate interactive water stress responses (McCree et al., 1990). It was noted that in sorghum, low stomatal conductance was the primary factor determining its low water use per carbon gain. This was the case in unstressed as well as stressed conditions (McCree et al., 1990).

Patterns of dry matter accumulation have been shown to be directly proportional to the amount of solar radiation intercepted by the crop (McGowan et al., 1991). More specifically, total dry matter is the product of intercepted, photosynthetically active radiation (PAR) and radiation use efficiency (RUE). The RUE was shown to differ by genotype in a grain sorghum study (Hammer and Vanderlip, 1989). There were also interactions with temperature, but the physiological explanations remain elusive. Temperature has an effect on the rate of development in grain sorghum (Hammer et al., 1989). This is particularly the case in the period of time between emergence and anthesis, a critical period when crop growth rates are highest in sorghum and the number of phytomers is determined. Temperature effects generally predominate over photoperiod effects in sweet sorghum development during this time also, as would be expected in the growth of an unmodified tropical species grown in the midwest. Photoperiod has been implicated as the dominant environmental influence during the reproductive period (Coleman and Belcher, 1952).

Ultimately, carbohydrate yields are greatest in sweet sorghum (and other sorghum) cultivars where phenological development is synchronized with an environment such that high incident radiation coincides with a long pre-anthesis growth period (Ferarris and Charles-Edwards, 1986b). Radiation received during fruiting has the greatest influence on dry matter yield. This was shown to be a linear relationship, where approximately 1.4 kg ha^{-1} of sweet sorghum was produced 4.2 J m^{-2} of solar radiation (Hipp et al., 1970). In forage and sweet sorghum cultivars, the rate of accumulation of sugars is constant, therefore dry matter differences are expressed in intercepted PAR-use efficiency terms (Ferarris and Charles-Edwards, 1986b). For sweet sorghum lines, 95 % of the PAR intercepted was utilized in increasing the pools of soluble sugars (versus 5 % for the forage type). On the other hand, PAR-use efficiency for N is not significantly different by sorghum type. The PAR-use efficiency also changed over time. It was greatest during maturation, when radiation and leaf area values are high and growth rates have decreased (Ferarris and Charles-Edwards, 1986a).

Several crop growth models have been proposed for sorghum. Shih et al. (1981) modeled the production of biomass in sweet sorghum cultivars. Early growth was dominated by leaf expansion; the later growth phase was characterized by high rates of stalk growth and dry matter accumulation. The pivotal components in establishing yields were dry leaf biomass accumulation, leaf dry biomass, leaf area index, and their specific relationships to total dry biomass. In addition to its use in simulating water use efficiency, the model by McCree et al. (1990) also considered the interacting effects of respiration on the carbon use efficiency in specific tissues. A linear function has been developed to describe the effect of daily average temperatures on the rate of development in grain sorghum (Hammer et al., 1989).

Bender et al. (1983) assumed that the phenology of sweet sorghum and grain sorghum is mostly determined by temperature. They proposed a growth model that used the modifications of leaf area to stalk length ratios as suggested by Shih et al. (1981). They also modified the leaf extinction calculation, and changed the proportion of dry matter partitioned between plant parts as compared to that used by Vanderlip (1972) for grain sorghum. Considering the fact that the flowering of sorghum population is not completely synchronous, the model predicted the half bloom stage with accuracy, as well as physiological maturity. Dry matter partitioning was also predicted with confidence. The proportion of dry matter diverted to the stalk was substantially greater than in previous models. A study by Wiedenfeld (1984) found that the dry matter production allocated to stalks in sweet sorghum ranged from 55 to 60 %, from 29 to 32 % for leaves, and from 5 to 12 % for panicles. Although more work needs to be done on the partitioning of dry matter into fermentable versus non-fermentable portions, the authors state that the model is adequate for use in scheduling sweet sorghum harvests (Bender et al., 1983).

Plant Composition

Sweet sorghum stalks are 5 to 10 % juicer than the "dry-stalked", predominantly grain-producing cultivars (Coleman, 1970). The sugar concentration at maturity ranges from 10 % to over 20 % of the plant sap. Glucose and fructose are the predominant reducing sugars in the leaves and stalk. Sucrose is the predominant disaccharide. Starch does occur in the leaves and stem, although the concentration of stalk starch has decreased with the breeding efforts made for suitable syrup cultivars (Wall and Blessin, 1970). A similar result has been seen with the levels of aconitic acid in the stalk tissue; it is undesirable in syrup production (Coleman, 1970). The starch content of the tissues decreases considerably as grain developed (Wall and Blessin, 1970).

In a study by Shaffer et al. (1992), cellulose, hemicellulose, and lignin made up 62.1 % of sweet sorghum stems and 54.1 % of the whole plant. The total structural component content was higher in stalks than in leaf blades; stalks had almost three times as much lignin as leaves. More cellulose was found in stalks than in leaf blades; the reverse was true for hemicellulose. The rind fraction of the stalk contained more structural components than the pith. These distribution relationships varied by cultivar (McBee and Miller, 1990). Non-structural carbohydrate levels were always higher in stalks than in leaves. Non-structural carbohydrate levels in leaf blades did not differ by cultivar. An inverse relationship between nonstructural carbohydrates and neutral detergent fiber concentration has been established (McBee and Miller, 1990). A negative correlation was observed between the partitioning of non-structural carbohydrate and structural carbohydrate; this relationship appears to be genetic and pleiotropic (Miller and McBee, 1993).

Little information is available on sweet sorghum culm anatomy. Sorghum stalks in general are characterized by relatively numerous stomates. Many sorghum cultivars have a thick waxy coating on the stem surface. The formation of air-filled, cottony tissue has been noted in some sorghum stems as they mature (Freeman, 1970). The accumulation of "diffuse" starch in the cells surrounding vascular bundles and in the parenchyma between the bundles occurs in sweet sorghum (Freeman, 1970). Sugarcane internodal tissue (with the rind removed) is composed of 90 % storage parenchyma cells and the remainder is xylem, phloem, and schlerenchyma. Vacuoles make up 80 % of the storage volume (Hawker, 1985).

Variations in leaf surface anatomy in sorghum may be helpful in classification (L. G. Clark, 1992, personal communication). The leaf midrib color in sorghum has been associated with various characteristics such as stalk juiciness (Quinby and Schertz, 1970) and digestibility (Kalton, 1988).

Mature sweet sorghum grain may contain raffinose and stachyose in addition to starch, protein, and sucrose. Given the wide range in panicle and grain sizes, protein production in sweet sorghum varies widely (Wall and Blessin, 1970). Glucose, fructose, and sucrose are the principal sugars in the developing sorghum caryopsis and the bracts-pedicel unit. During seed formation, the concentration of reducing sugars is higher than that of sucrose in both organs. When starch begins to accumulate in the caryopsis, the level of sucrose in the caryopsis also rises and the amount of starch in the bract-pedicel decreases (Singh and Asthir, 1988). The percentage of total carbon partitioned to grain was similar if not greater in a study comparing a sweet sorghum hybrid with a grain sorghum hybrid (Vietor and Miller, 1990).

The concentration of nonstructural carbohydrates was also 1.4 and 2.7 times higher in the upper and lower internodes respectively of a sweet hybrid when compared to a grain hybrid. This indicates a higher potential for concentrating these carbohydrates in the sweet hybrid and/or a larger storage sink (Vietor and Miller, 1990). Some sweet sorghum cultivars partition a significant amount of carbon to branches at the upper internodes. In general, mature stem tissue and branches proximal to the source leaf are sinks for non-structural carbohydrate (Vietor and Miller, 1990). In another study, deheading a sweet sorghum cultivar increased the stalk sugar concentration but decreased the water content; therefore the sugar yield was not affected. However, lodging was decreased and branch production increased (Broadhead, 1973).

The concentration of different sugars varies as the sweet sorghum plant develops. The total sugar concentration between the dough stage and physiological maturity nearly doubles over that between the milk and dough stages (Wall and Blessin, 1970). Lingle (1987) found a seven-fold increase in sucrose concentration between the boot and mid-grain filling stages. The total sugar content of whole stalks was lowest at the boot stage and highest at soft dough. Sucrose predominated at all stages although it was only 50 % of the total soluble sugar in plants in the boot stage; glucose and fructose accounted for the remainder. Glucose was slightly higher than fructose at all stages; they both decline after anthesis (Lingle, 1987). McBee and Miller (1982) found that sucrose exhibited the most consistent diurnal and seasonal patterns at anthesis of all the sugars; glucose had the most variation due to its high demand in other metabolic pathways.

A highly significant positive correlation (r= +0.98) was found between sucrose and total sugars (Krishnaveni et al., 1990). The amount of sucrose synthesized in the tissue of mature plants exceeds that which could have been accounted for by the decrease in reducing sugars (Ventre et al., 1948). McBee and Miller (1982) suggested that sweet sorghum cultivars may inherently vary in production of mono and disaccharides and relative degree of senescence. They found this to be specifically true for glucose concentration.

Finally, soluble carbohydrate concentrations are not uniform within the culms of sweet sorghum cultivars (McBee and Miller, 1982). It has been noted that the upper internodes have a higher total sugar concentration and higher sucrose concentration than the lower internodes at physiological maturity (Coleman, 1970). In plants with eleven internodes, the highest concentration of sugar was found in internode seven (Krishnaveni et al., 1990). The distribution of carbohydrate also changes over time. Prior to the boot stage, the final internodes are still elongating and laying down new tissue. These internodes became the most enzymatically active and strongest sinks (Lingle, 1987). The onset of the reproductive phase is associated with the accumulation of sucrose and the termination of internodal growth. Before anthesis, sucrose accumulation is slow due to the competition of elongating internodes; after heading sucrose accumulates because the panicle is a less competitive sink (Lingle, 1987).

Sucrose storage in sweet sorghum appears to be biochemically different than in sugarcane. In a study by Lingle (1987), there was no relationship between sucrose concentration and neutral invertase activity, or between sucrose-phosphate synthase and sucrose accumulation. This is an indication that sucrose cleavage is not required for uptake in sweet sorghum parenchyma as it is in sugarcane (Lingle, 1986). These results suggest diffusion as a transport mechanism for sucrose in sweet sorghum, or an active sucrose transporter at the plasmalemma or tonoplast. The differences in sugar accumulation in sweet sorghum and sugarcane stalks may be due to differences in the competitiveness of elongating and mature internodes (Lingle, 1987).

In a study comparing sweet and grain sorghum cultivars, elongating internodes had the highest activities of acid and neutral invertase and sucrose synthase, with almost no accumulation of sucrose (Tarpley et al., 1994). A metabolic change occurred with the onset of reproduction and non-structural carbohydrate storage. In the panicle, acid invertase, neutral invertase, and sucrose synthase activity increased with the rapid growth of the inflorescence, then declined during grain filling. Soluble invertase, not sucrose synthase, was suggested as the first step in sucrose metabolism in the panicle (Tarpley et al., 1994). In the culm, a decline in sucrose synthase levels as well as the low activity levels of the invertases appears to be an irreversible event and a prerequisite for the transition from internode growth to sucrose storage (Tarpley et al., 1994). These low enzymatic activity levels suggest that the sorghum stalk is a quiescent sink, as described by Sung et al. (1989). However, the decline in sucrose-degrading activities did not account for differences among sorghum cultivars in sucrose storage ability; mechanisms beyond sink strength and enzymatic activity are necessary to explain the higher rates of sucrose accumulation in sweet sorghum than in grain sorghum (Tarpley et al., 1994)

Sweet Sorghum Culture

The number of hectares in sweet sorghum production in the USA peaked at 141,643 in the 1930's (Coleman, 1970). There was a precipitous drop to less than 405 hectares planted in 1987 (Bureau of the Census, 1987). Interest in sweet sorghum production has been renewed due to its drought tolerance and high N and radiation use efficiencies. Currently, it is predominantly used for feed in the south, either as silage or for syrup to sweeten grain feeds. Interest in local production for human use as a sweetener with nutritional value has also increased (Kuepper, 1992).

Historically, sweet sorghum production for syrup has involved specific cultural practices. Producers observe that excess nitrates and cultivar selection both affect syrup quality. Syrup producers generally apply 34 to 56 kg ha^{-1} of N (Kuepper, 1992). Some use planting patterns to facilitate the removal of panicles and leaves at harvest. One such pattern is skip-row planting where four 75 cm rows are planted and two are left open, with no reduction in yield. Sweet sorghum production has traditionally been incorporated into an appropriate crop rotation

(Kuepper, 1992). Management is generally determined by an emphasis on maximum total yield, not by a particular plant organ or an aesthetic attribute.

Studies have shown that early planting increases sugar yields at harvest (Lueschen et al., 1991, Broadhead, 1969). Fermentable carbohydrate concentrations were increased by 13 % in early plantings over late plantings (Lueschen et al., 1991). However, soil temperatures should be at least 65°F at planting time to ensure adequate stands. Sorghum seedlings are not vigorous in cool, wet conditions (Kuepper, 1992). In general, planting dates should be planned such that close to the maximum solar radiation is received by the crop in the period between boot and early seed formation (Hipp et al., 1970).

Numerous studies have been done on the effects of plant spacing on sugar yields in sweet sorghum. Lueschen et al. (1991) and Broadhead et al. (1963) found that planting densities only slightly affect sweet sorghum sugar yields. Seed cost became the more important factor. In a grain sorghum study, McGowan et al. (1991) found no advantage in planting in wider rows (1.5 m); dry matter production was lower in sorghum grown in wider rows. McBee and Miller (1982) found that plants in narrower rows (10 cm) had higher total non-structural carbohydrate levels both preboot and at anthesis than those in wider (40 cm) rows. In another study, Miller and McBee(1993) found that wider spacing increased the structural carbohydrate levels. Therefore, they concluded that planting geometries could be used to alter the partitioning of photosynthate to structural or non-structural carbohydrates. There may be additional benefits in adjusting plant spacing, such as improving water-use efficiency and decreasing lodging (McGowan et al., 1991).

In general, dry matter accumulation is related more directly to the amount of solar radiation intercepted than to row spacing. Sorghum plants adapt by an unknown mechanism to the row width and population density by altering leaf and tiller production (McGowan et al., 1991). Ultimately, sugar yields are determined by stalk diameter/storage capacity and the ability to produce tillers (Coleman, 1970).

General experience has shown that sweet sorghum requires only moderate amounts of N. Several cultivars responded to 112 kg N ha^{-1}, often in distribution of biomass between plant tissue types (Wiedenfeld, 1984). Smith and Buxton (1993) found that N amendments had no significant effect on sugar yields. Lueschen et al. (1991) also noted that N fertilization was not a determinant of the ethanol potential of sweet sorghum. The residual soil N levels of 90 kg ha^{-1} appeared to be sufficient. California studies have shown that sweet sorghum requires 37 % of the fertilizer N used by corn (Hills et al., 1990).

Sweet sorghum can be sown and cultivated with conventional equipment. Sweet sorghum planting can be scheduled after other crops have been planted. Since it is largely a self-pollinated plant, seed can be saved each year for the following cropping season. There is also little variance in the number of seeds kg^{-1} per cultivar (Kuepper, 1992). The recommended row width is 75 to 100 cm and recommended densities are similar to grain sorghum, or 6 to 10 plants row-m^{-1} (Kuepper, 1992). These cultural characteristics along with modest water requirements indicate that sweet sorghum production is potentially energy and cost efficient.

Harvest, Transport, and Storage

Lueschen et al. (1991) found that fermentable carbohydrate concentrations in sweet sorghum reached a maximum and then declined. For their study, in the upper midwest, the maximum was reached in mid-September through early October for several cultivars. The recommended harvest date would coincide with this maximum. Broadhead (1969) reported that the time of harvest had no effect on stalk sugar yield. The crop was harvested up to 3 wk after the seeds were ripe with no effect on soluble carbohydrate levels. Syrup producers use the soft dough stage as their guide for harvesting; they use a 2 wk window around this time (Kuepper, 1992). Producers commonly monitor sugar concentrations by taking Brix readings with a refractometer (Brix is a measurement of the mass of solids as a percentage of the total mass of the solution; for sugar crops, the dissolved portion of the plant sap is essentially sugars). The harvest period could be extended by using cultivars with varying maturities or by harvesting a portion of the crop early, if economically acceptable sugar levels have been reached. It is also advantageous to postpone harvest until a maximum percent dry matter of sugars has been reached, since transportation and handling costs will increase with the amount of water in the crop (Lueschen et al., 1991). The length of the growing season in the southern USA allows successional harvests of the same sweet sorghum plants, a process called ratooning. Yields are often increased by using this method (Miller and McBee, 1993).

Harvest and storage methods are both dependent on the type of ethanol production system used. The ultimate goal is maximum preservation of soluble carbohydrate. The choice of solid-state fermentation or juice fermentation will determine the harvest procedure. If the juice is to be fermented, then a method of harvesting the whole stalk or sectioning the stalk is chosen. Traditionally syrup producers harvested stalks whole after stripping the leaves and deheading by hand. Currently, row binders are often used with other modified machinery to remove the panicles and leaves (Kuepper, 1992). More advanced whole-stalk harvesters have been designed (Rains et al., 1990). Field machines have also been designed to cut the plants, remove the panicles and section the stalks in one pass (Monroe and Sumner, 1985). Whole stalks are dumped into windrows or bundled, whereas harvested stalk sections, or billets, can be handled with self-unloading forage wagons (Monroe and Sumner, 1985). The plant material is then delivered to a centralized shredder, mill or storage facility. Sugarcane harvesting and transport equipment has been shown to be satisfactory for processing biomass crops such as sweet sorghum (Clayton and Eiland, 1984).

Recent efforts have focused on removal of the rind fraction of the stalk from the pith to facilitate juice expression and to increase the sugar concentration in the extract. In the Tilby system, stalk billets are split lengthwise and the pith is scraped out and processed separately. This process proved effective in increasing the amount of fermentables extracted from sweet sorghum stalks (Reidenbach and Coble, 1985). Crandell et al. (1989) used a set of modified stalk walkers to separate the two fractions. They also had improved expression of fermentables with the pith fraction when compared with whole stalk expression. McBee et al. (1988) suggested that removal of the rind may remove inhibitors to yeast fermentation. A pith combine system was proposed by Worley and Cundiff (1992) where the rind-leaf fraction would be dropped in the field and the pith would be pressed.

Stalk storage as a method of preservation has had varying results. Broadhead (1969) found that storage of whole stalks beyond 48 h lead to a decrease in sap purity (a measure of sucrose concentration), due to the inversion of sucrose. Those stalks that were immature did not store as well as those that had reached maturity (Broadhead, 1972). However, Brix readings of the stalks did not decrease; in some cases Brix values increased slightly with storage time (Broadhead, 1969). These results were also reflected in a study by Hansen and Ferraris (1985). Retention of sucrose would be important to sugar producers; inversion of sucrose is not a problem for ethanol production.

Eiland et al. (1983a) reported differences in the storage qualities of stalks cut into various sizes. Stalks and billets (0.6 m lengths) were stored successfully for as long as 1 wk with no loss of fermentable carbohydrate yield. Material harvested with a forage chopper (0.5 to 5.0 cm lengths) lost sugars rapidly in the first 24 h (Eiland et al. 1983a). In a study of billets of two sizes (28 cm and 50 cm) and whole stalks, whole stalks lost weight but maintained juice quality longer than both billet sizes (Eiland and Clayton, 1984). Some of the storage methods listed above along with an extended harvest period might allow a 50-d processing period (Eiland et al., 1983a). Chopped material would need to be processed immediately if left untreated. Billet size also has implications for ethanol conversions efficiency (Reidenbach and Coble, 1985).

If solid-state fermentation, or storage as chopped material is under consideration, a standard forage harvester can be used to harvest the whole plant. Chopped material can be stored in fermentors/harvestores or bunker/trench silos. Amendments have been investigated to improve storage as silage. Fermentable losses were reduced by sulfur dioxide introduced at 4000 mg kg^{-1}; chopped sorghum was preserved for over four months. Juice from the preserved material was then treated with lime. The liquid minus the precipitate was fermented to ethanol with no reduction in yield (Eiland et al., 1983b). Native yeast strains readily ferment sweet sorghum solids in anaerobic storage within 60 to 120 h (Bryan, 1990). With bulk inoculations of cultured yeast strains and acidification, carbon losses through other metabolic pathways are minimized, preservation maximized and ethanol yields increased (Bryan, 1990).

Transportation of harvested material is potentially costly because of the large water concentration of the crop at harvest. Transportation cost would be dependent on the travel distance to a centralized processing facility. Travel distance, in turn, would be determined by the percentage of local area planted to sweet sorghum and road conditions (Worley and Cundiff, 1992). Cundiff and Vaughan (1984) stated that if an average of 4 % of the fuel potential in sweet sorghum is used in its transportation, than a central mill for processing stalks could serve an area of 12 km in radius. A 16 km standard is also mentioned (Worley et al., 1992b).

Harvest and storage methods depend on the intended use of the crop, if there are co-products, transportation, and timing of extraction of fermentables. Overall, harvesting systems for sweet sorghum as an energy crop include: 1) immediate pressing of stalks and fermentation of the juice, use of the bagasse as feed, a soil amendment, or as a source of thermal energy (e.g., Rajvanshi et al., 1989); 2) fermentation of the juice at harvest and use of the cellulosic by-products throughout the year (e.g., Worley et al., 1992a); 3) preservation of the juice extracted at harvest to be fermented throughout the year (e.g., Worley et al., 1992a); 4) chopped silage harvested, inoculated and fermented, the ethanol removed by a screw press or by flash evaporation and the bagasse used as a source of thermal energy (e.g., Bryan et al., 1985); 5) billets shredded and milled, the bagasse inoculated, and fermented juice removed by a press (e.g., Bryan et al., 1985); 6) small chips milled immediately, juice fermented and the bagasse ensiled for feed (e.g., Worley et al., 1992a; 6) rind removed from stalks and pith processed (e.g. Worley and Cundiff, 1992); and 7) stalks milled, bagasse dried and baled, with both products containing fermentables (e.g., Bryan et al., 1981, Clayton and Eiland, 1984).

Ethanol Conversion Efficiency

The sugars in sweet sorghum sap are directly and readily fermentable. Potential ethanol yields ranged from 3100 to 5235 L ha^{-1} in one study (Smith and Buxton, 1993) and from 2129 to 5696 L ha^{-1} in another investigation (Smith et al., 1987). This compares with a value of 2581 L ha^{-1} for the ethanol potential for corn as determined by Putnam et al. (1991). In general, high yields are associated with late-maturing, high sugar-yielding cultivars (Putnam et al., 1991). The relationship of ethanol yield with sugar concentration was described by the linear regression: Ethanol, % (of juice) = - 2.59 +0.51°B, where °B was the Brix of the original plant sap (Eiland et al., 1983a). Fermentation or ethanol production efficiency has been calculated using several methods.

Conversion efficiencies are based on a ratio of 5.68 kg of sugar to produce one L of ethanol (Smith and Buxton, 1993) or one kg sugar for the production of 0.576 L of ethanol (Worley et al., 1992b). Of this, often only 80 % of the total mole equivalence of the two compounds is included; this accounts for losses due to inefficient sugar extraction, the fermentation process, and carbon consumed by microorganisms (Smith et al., 1987). Commonly, energy efficiency is expressed as the ratio of energy produced to the total energy inputs. The ethanol production efficiency factor varies depending on the extraction and fermentation methods used.

Worley et al. (1992a) compared two theoretical methods for conversion efficiency: 1) extraction juice was evaporated to syrup and stored for year-round fermentation and the bagasse was used as fuel for the distillation process, and 2) the juice was fermented at harvest and the cellulosic remainder was stored as a continuous ethanol feedstock. The second option yielded the most ethanol but was the most costly. It did have a positive net energy ratio of 1.1 versus a less then one value for the first method and for the same calculations using corn grain as a feedstock. The 1.1 value increased to 7.9 when only liquid fuel-derived inputs were considered in the calculations. Alternatively, energy balances can be viewed in terms of fossil fuel consumption. Mitchell et al. (1983) determined the oil replacement energy balance to be equal to the ratio of the petroleum consumed to the equivalent oil replaced.

Farm-scale three-roll mills are commonly used in liquid fermentation of juice from sweet sorghum stalks. Bryan et al. (1981) obtained extraction rates of 43 % of the stalk sugar (or one third of the stalk weight) with such a mill, followed by a distillation rate of 81 %. A sugar recovery rate of 79.9 % was obtained by pressing chopped stalks in a cage press. Juice from milled whole stalks yielded a 90 % conversion efficiency in a study where the bagasse was also given a value as livestock feed (Rajvanshi et al., 1989). Reidenbach and Coble (1985) achieved an extraction rate of 54.6 % for sweet sorghum stalks using a roller mill for juice extraction. This method was compared with a pith separation method where the production efficiency was reduced. While alcohol loss in the juice extraction process did occur, Reidenbach and Coble (1985) recommended the juice extraction method based on the ease with which the juice could be handled and the lower process volume and waste. Multiple pressing in three-roll presses and the use of continuous presses have been shown to increase sugar recovery (Bryan et al., 1981). A shredder-mill has shown greater extraction efficiency when compared with pressing whole stalks; it worked best with high feed rates (Monroe and Bryan, 1984). Some sweet sorghum cultivars have higher extraction rates then others when pressed (Eiland and Clayton, 1984).

The energy efficiency of pith and rind separation and fermentation has been considered. Worley and Cundiff (1992) proposed both separating the pith, processing it with a screw press and leaving the leaf-rind portion in the field versus saving the leaf-rind fraction (25 % of the plant) to be ensiled with the bagasse for future use. Neither of these methods appeared to be economically feasible. The pith fraction was successfully separated from the rind in an experiment using chopped material (Cundiff and Vaughan, 1984). The pith contained 80 to 90 % of the total fermentables. This process would be economical only if milling efficiencies were increased by an amount of energy equal to that which went into the chopping and separating operations (Cundiff and Vaughan, 1984).

Bryan et al. (1985) compared the direct fermentation of chopped sweet sorghum with that of shredded and milled billets, followed by fermentation of the bagasse. The fermentation rate was higher in the chopped stalks than for the bagasse, reaching 90 % conversion in 38 h. The fermented bagasse reached a 90 % conversion level in 72 h. The fermented juice was then expressed with a screw press with efficiencies of 54 to 70 %; the energy required in pressing the bagasse was four times greater than that required for the chopped stalks. Reidenbach and Coble (1985) noted that juice extraction was the poorest method for carbohydrate extraction. The smaller the stalk particle, the more readily the sugar diffused from the stalk to be metabolized. However, they noted that pressing the chopped material required over three times as much process water as did the extracted juice.

Since 4 to 9 % of the total plant sugar occurs in the leaves and panicles of sweet sorghum, increasing the sugar recovery rates requires a method using the whole plant (Monroe and Bryan, 1984). Indeed, the net energy balance becomes more positive and a given method more economical when as much of the plant as possible is considered for energy derivation. However, Miller and McBee (1993) suggested that the inclusion of leaves in the harvested biomass can also affect the quality of the juice, the concentration of soluble carbohydrates, and that it may be more profitable to use the leaves as a soil amendment. The energy balance would also increase where credit was given for use of part of the crop for livestock or some other multiple use. In a comparison of four methods, forage chopping and juice extraction was the most economical (Worley and Cundiff, 1992). The remaining plant material is available for cellulosic fermentation or as a source of heat for the distillation process.

The largest area in need of improvement is the fermentation-distillation process of sweet sorghum. About 70 to 85 % of the total energy consumed in alcohol production occurs at this step (Rajvanshi et al., 1989). A value of 1.6 has been obtained for the ratio of energy output to energy consumed in processing ethanol from sweet sorghum (Nan and Ma, 1989). Losses are attributed to the production of byproducts such as glycerol and lactic acid (Bryan et al., 1985) and to the evaporation of acetaldehyde with the CO_2 evolved (Bryan, 1990). Other losses occur in the handling of fermented material. The development of closed handling systems and of new, more efficient yeast strains (deMancilha et al., 1984a, and deMancilha et al., 1984b) will aid in decreasing these losses. Advances have been made in the conversion to ethanol through the use of immobilized yeast cells (Mohite and SivaRamen, 1984) and of a rotary-drum fermentor (Kargi and Curme, 1985). There is also potential in the more complete utilization of the often substantial amount of starch in the grain of sweet sorghum (Kalton, 1988).

Numerous methods have been proposed for the processing of the fibrous residue or structural portion of the sweet sorghum plant. Worley et al. (1992b) found that producing hay from the rind-leaf fraction was not an economically competitive option, nor was paper production from the hay. They found that the ensiled residue remaining after the juice was removed and fermented could compete when used as cattle feed and processed in a fiber conversion plant, in combination. Progress has been made on enzymatic hydrolysis of cellulosic fibers within a simultaneous saccharification and fermentation process (Wright, 1988). Acid hydrolysis of cellulosic material prior to fermentation has also been successful (Harris and Rosen 1992) and implemented on an industrial scale. Substantial amounts of xylose formed in the pretreatment of the fibrous component could also be fermented. The lignin fraction is available for conversion to high-octane material after pretreatment as well (Wright, 1988). The energy derived from the combustion of the fibrous rind of a sweet sorghum cultivar was almost two times that available in the alcohol produced by that cultivar (McBee et al., 1988). That energy would be available for distillation or for generating other forms of energy. Research on anaerobic treatment of stillage for methane gas production has also shown high conversion efficiency, as well as a reduction in the cost of ethanol production (Stover, 1986). Other systems based strictly on methanogenesis from sweet sorghum have also been explored (Egg et al., 1984, Sweeten et al., 1985).

MATERIALS AND METHODS

Site Description

The cultivar experiments were conducted in 1991, 1992 and 1993. Twelve cultivars were grown at two locations in Iowa. They were the Agronomy and Agricultural Engineering Research Center near Ames in Boone County and the McNay Memorial Research Center near Chariton in Lucas County. The two sites are separated by approximately 145 km. These sites were chosen because of their different production expectations for growers, based on land type and fertility factors.

The Agronomy and Agricultural Engineering Research Center (AAERC) is at 42° N latitude and 93° W longitude. The fields used in 1991 and 1992 were primarily Nicollet loam (fine-loamy, mixed, mesic Aquic Hapludolls), Harps loam (fine-loamy, mesic Typic Calciaquolls), and Canisteo silty clay loam (fine-loamy, mixed [calcareous], mesic Typic Haplaquolls). This land has 0 to 3 % slope and is in the Land Capability Classes 1 and 2. The organic matter content ranges from 4 to 8 %. In 1993, the plots were on Webster silty clay loam (fine-loamy, mixed, mesic Typic Haplaquolls) and Canisteo silty clay loam (fine-loamy, mixed [calcareous], mesic Typic Haplaquolls) and had a 0 to 2 % slope. This area has a Land Capability Classification of 2 and is 6 to 8 % organic matter. The area is characterized by poor drainage (unless altered) and a high available water capacity and cash crop production.

The year before the sweet sorghum plots were sown, the fields were in the soybean component of an oat-corn-soybean rotation. The average frost-free growing season is 160 d. Rainfall average is 813 mm per year. For more information on average monthly rain and temperature and departures by year see Tables 1 and 2.

The McNay Memorial Research Center (McMRC) is at 41° N latitude and 93° W longitude. The field used for all 3 years was predominantly a Grundy silty clay loam (fine, montmorillonic, mesic Aquic Argiudolls) grading into an Arispe silty clay loam (fine, montmorillonic, mesic Aquic Argiudolls). This land has 2 to 9 % slope and has a Land Capability Classification of 2 and 3. The organic matter content ranges from 2 to 4 %. These soils are somewhat poorly drained and have erosive tendencies. Production in the area is primarily devoted to livestock.

The plots were in conventionally managed red clover (*Trifolium pratense* L.) and then 1 year of oat production before sweet sorghum planting. The sweet sorghum plots were on the same site for all 3 years. The average frost-free growing season is 165 d. Precipitation averages about 864 mm per year. (See Tables 3 and 4 for more weather data.)

Plant Material and Experimental Design

Twelve cultivars of *Sorghum bicolor* (L.) Moench, subrace Sorgo, were selected to include a wide range of maturities, morphologies and breeding histories. Three cultivars, Dale, Theis and M81E, originated at the Mississippi Agriculture and Forestry Experiment Station (MAFES) at Meridian. This station has

Table 1. Monthly precipitation and departure form a 29 year average at the Agronomy and Agricultural Engineering Research Center (AAERC), Ames, Iowa.[1]

Year	1991		1992		1993	
Month	Precip.	Depart.	Precip.	Depart.	Precip.	Depart.
	mm					
January	19	1	31	12	32	13
February	4	-20	39	15	31	7
March	124	71	63	10	128	76
April	233	147	99	13	101	14
May	132	21	26	-85	288	177
June	106	-24	15	-115	300	158
July	44	-43	259	171	645	558
August	93	-6	57	-42	410	311
September	60	-22	104	22	157	76
October	85	26	14	-45	60	1
November	70	36	117	83	44	10
December	43	21	46	24	24	2
Annual	816	12	868	64	2219	1415

[1] Excerpted from NOAA Climatological Data for Iowa ISSN 0145-0468, Vols. 102-104 Nos. 1-12.

Table 2. Monthly temperature and departure from a 29 year average at the Agronomy and Agricultural Engineering Research Center (AAERC), Ames Iowa.[1]

Year	1991		1992		1993	
Month	Temp.	Depart.	Temp.	Depart.	Temp.	Depart.
	°C					
January	-10.3	-2.1	-1.9	6.3	-7.8	0.5
February	-0.9	3.8	0.0	4.8	-7.5	-2.7
March	4.6	3.5	4.6	3.5	-0.3	-1.4
April	11.3	1.6	8.5	-1.2	7.6	-2.1
May	18.3	2.2	16.6	0.4	15.7	-0.5
June	23.3	2.2	20.7	-0.5	20.1	-1.1
July	23.3	-0.1	20.4	-2.9	22.4	-0.9
August	21.9	-0.2	18.9	-3.2	21.9	-0.2
September	17.5	0.0	16.9	-0.6	14.8	-2.7
October	10.6	-0.9	11.0	-0.6	10.4	-1.2
November	-2.0	-6.2	0.4	-3.7	1.4	-2.8
December	-2.4	1.9	-4.4	-0.2	-3.2	1.1
Annual	9.6	0.5	9.3	0.2	8.0	-1.1

[1] Excerpted from NOAA Climatological Data for Iowa ISSN 0145-0468, Vols. 102-104 Nos. 1-12.

Table 3. Monthly precipitation and departure from a 29 year average at the McNay Memorial Research Center (McMRC), Chariton, Iowa.[1]

Year	1991		1992		1993	
Month	Precip.	Depart.	Precip.	Depart.	Precip.	Depart.
	mm					
January	20	-7	19	-8	48	21
February	5	-23	47	18	35	7
March	103	40	39	-23	119	56
April	228	136	144	52	126	34
May	102	2	34	-67	231	130
June	66	-57	15	-108	137	15
July	60	-38	166	68	691	593
August	62	-40	49	-53	326	224
September	32	-81	319	206	154	41
October	96	30	9	-57	43	-23
November	99	55	111	66	34	-10
December	38	8	39	9	19	-11
Annual	912	27	989	104	1962	1077

[1] Excerpted form NOAA Climatological Data for Iowa ISSN 0145-0468, Vols. 102-104 Nos. 1-12.

Table 4. Average monthly temperature and departure from a 29 year average at the McNay Memorial Research Center (McMRC), Chariton Iowa.[1]

Year	1991		1992		1993	
Month	Temp.	Depart.	Temp.	Depart.	Temp.	Depart.
	°C					
January	-9.5	-3.1	-1.9	4.6	-6.7	-0.3
February	-0.5	2.4	1.4	4.3	-6.2	-3.3
March	5.2	2.4	5.3	2.5	0.9	-1.9
April	11.3	0.4	8.3	-2.6	7.7	-3.1
May	18.3	1.7	14.8	-1.7	15.4	-1.2
June	22.3	0.8	18.9	-2.6	19.9	-1.6
July	23.5	-0.5	21.5	-2.5	22.7	-1.3
August	22.4	-0.4	19.0	-3.8	23.1	0.3
September	18.0	-0.3	16.4	-1.9	14.4	-3.9
October	10.3	-2.1	11.0	-1.3	9.9	-2.4
November	-1.4	-5.6	1.6	-2.6	2.0	-2.2
December	-1.4	-5.6	1.6	-2.6	-2.4	0.2
Annual	12.3	2.2	9.4	-0.7	8.4	-1.7

[1] Excerpted form NOAA Climatological Data for Iowa ISSN 0145-0468, Vols. 102-104 Nos. 1-12.

been the most active site for production and improvement of the "energy" sorghums and is currently doing selections. The cultivars Rio (originally released for use as a sugar crop), Smith and Grassl were supplied by the Weslaco Experiment Station in Weslaco, Texas. Grassl is one of several accessions that have remained as they were when collected in Africa. It originated in Uganda. Three other cultivars obtained from the Weslaco station in Texas were Cowley, Keller and Wray. These cultivars were developed in the 1970's and 1980's. Seed for the cultivars Kansas Orange, Waconia, Sugar Drip, and Rox Orange was obtained from the Rose Seed Company in San Jon, New Mexico. Rox Orange was substituted for Rio in 1993, because of the lack of a seed source for Rio. Sugar Drip and Rox Orange are considered heirloom cultivars. Rox orange was improved at the Wisconsin Agricultural Experiment Station and Waconia was improved in Iowa. Sugar Drip has been used in the USA throughout its sorghum syrup producing history. Several in this group are dual purpose forage and syrup cultivars.

The AAERC fields were chisel plowed in the fall. The seedbed was prepared in the spring with a field cultivator and a harrow in one pass. Fertilizer rates by year can be seen in Appendix A. The seed was safened with Concep (alpha-[(1,3-Dioxolan-2-yl-methoxy)imino] benzene-acetonitrile; Appendix A). A corresponding rate of the herbicides Lasso (2-chloro-N-[2,6-diethylphenyl]-N-[methoxymethyl] acetamide) or Dual 8E (2-chloro-N-[2-ethyl-6-methylphenyl]-N-[2-methoxy-1-methyl=ethyl] acetamide; Appendix A) was applied each year. A two-row cone planter was used to plant the two-row plots. The seeding rate goal was 16 plants per linear m of row, in rows spaced 75 cm apart. Hand planting or thinning was done to achieve this density. In 1991 the plots were 8.5-m long, but in 1992 and 1993 the length was decreased to 6.1 m. Planting and harvest dates can be seen in Appendix A.

At the McMRC, the same cultivars but different tillage practices were used. The field was disked and harrowed in the spring. Chemical applications are shown in Appendix A. The same planter and plot sizes were used as at AAERC. Planting and harvest dates are shown in Appendix A. All fields were cultivated once each season for weed control. Some hand weeding and hoeing of alleys was done.

The experimental design at both locations was a randomized complete block design. There were four replications at both sites in all years (except in 1991 at the AAERC) with 12 cultivars. In 1991 at AAERC, five replications were planted and two were harvested.

Field Data Collection

Several types of data were collected throughout each season: 1) stand counts were taken by marking 3-m sections in two replications at both sites, counting main stalks at the beginning of the season and the total number of stalks at the end of the season, 2) leaf and stalk unit development was measured by marking the fifth leaf early in the season, counting leaves and visible nodes and measuring plant height (to the last fully developed leaf collar) approximately every 10 d on five plants in two replications, 3) Brix (percent soluble carbohydrate) readings were taken using stalk cores removed with a size 5 cork borer on a schedule as follows: in 1991 readings commenced in three replications when the early cultivars were in bloom and continued until harvest; in 1992 and 1993 readings were taken in two replications as each cultivar came into the boot stage until harvest, 4) maturation patterns were tracked through the season for each cultivar by noting the date that 50 % of each plot was in a given stage, 5) percentages of plants lodged grater than a 45° angle were estimated visually for all replications at harvest and 6) whole plots were harvested with a two row John Deere forage harvester and weighed.

A hand refractometer (model 10430, AO Reichert Scientific Instruments, Buffalo, NY) with a scale of 0 to 30 % was used to take the Brix readings. This instrument was calibrated to measure the total dissolved solids in aqueous solutions. The calibration was verified at the beginning of each field season by using sugar standards of known concentrations. Actual measurements were taken at Internodes 4 and 8 on 2 plants in the replications noted above. These readings were taken every 7 to 10 d. In this study, it was assumed that the Brix values corresponded to the dissolved sugars in the plant sap.

At harvest, representative subsamples were weighed at 800 to 900 g from each plot and microwaved (1991 and 1992) for 6 to 8 min to reach an internal temperature of 100° C to suppress respiration in the plant tissue. The samples were then dried at 60° C for 48 h. After drying to approximately 3 % plant water, the subsample was weighed again for dry matter yield determination. The material was then ground two times, first in a Wiley mill (Thomas Manufacturing, Philadelphia, PA) to a size passing through a 5-mm screen and secondly through a Udy Mill (Udy Manufacturing, Fort Collins, CO) to finally pass through a 1-mm screen. Approximately 20 g of dried plant material was stored in glass jars or whirlpac bags for subsequent chemical (compositional) analysis. After finding that the glucose to sucrose ratios for 1991 and 1992 samples were not as expected, a portion of the subsample was frozen with ice directly from the field in 1993. This portion was used for laboratory analysis and the remainder was treated as stated above to determine dry matter yields.

Subsamples of two replications of the cultivars harvested at Ames were ensiled for alcoholic fermentation in all 3 yr. In 1991 and 1992, 16 kg of material per cultivar was inoculated with approximately 2000 cells of the yeast strain *Saccharomyces cerevisiae* NRRL Y-2034 g^{-1} of forage, acidified to a pH of 3.8 to 4.1 with sulfuric acid, and packed into 20 L containers. In 1993, 600 g of material was inoculated, acidified and packed into 1-L jars. Anaerobic conditions were achieved in all years by the introduction of dry ice. The "mini-silos" were sampled at approximately 2 and 4 months of age.

Laboratory Methods and Statistical Analysis

Dried plant samples (or frozen, from 1993) were analyzed for sugars using the Somogyi method for determination of reducing sugars as modified by Nelson (1944). The dried samples were prepared for this method by heating them in distilled water in a 100° C water bath for 20 min followed by filtration. The frozen samples were kept cold while homogenized in a blender prior to the water bath treatment. Subsequently, they were filtered and centrifuged. The concentration of the reducing sugars was measured spectrophotometrically. A second aliquot of each sample was prepared for the hydrolysis of sucrose by HCl in 1991 and 1992. In 1993, the second portion was treated with invertase for sucrose hydrolysis. The optical amount of sugar in the second sample was subtracted from the amount in the first sample to obtain a value for sucrose. When read at 660 nm and with a phosphate buffer solution, the range of detection was as little as 0.01 microgram to as much as 3.0 mg of glucose and other sugars (Somogyi, 1945).

Optical density values were converted to concentration in microgram L^{-1} by calculating a regression from standard solutions of glucose and sucrose. Sugar concentrations of samples were calculated using the linear regression obtained with the standards. Finally, percentages were calculated and sugar yields on a land area basis determined. Sugar analysis was performed on all plots of all replications at each location.

The fermented silage samples were analyzed for residual sugar by the colorimetric method as described above. High Pressure Liquid Chromatography was used to analyze for ethanol and volatile fatty acid concentrations. An Ion-300 column (Interaction Chemicals, Inc., Mountain View, CA) was used with .01N sulfuric acid as the eluent. Potential ethanol production was calculated using the total sugar yields for the two cultivar replications that were fermented. A conversion efficiency measurement was determined by dividing the amount of ethanol produced by the amount of potential ethanol. Net ethanol values were calculated by subtracting the energy consumed by crop production inputs from the ethanol produced. The input energy included: land preparation operations, fertilizer, pesticides and harvesting the crop (Ayres and Hanna, 1989).

The General Linear Model Procedure and Analysis of Variance Procedure (SAS Institute, Cary, N. C.) were used to determine the statistical significance of cultivar, location and year on the characteristics of the cultivars. Eleven cultivars were included in the analysis, due to the seed source problems. Yield characteristics for Rio and Rox Orange are shown in Appendix B. Various comparisons of individual cultivars and groups of cultivars were analyzed for differences. Seasonal Brix values and plant morphological measurements were considered as repeated measures and analyzed as such as well as in a qualitative discussion of linear regressions. Morphological measurements were analyzed for 1992 and 1993. The Analysis of Variance Procedure was used to determine cultivar and year differences in silage components. Stand counts and lodging measurements were not analyzed statistically but are presented in Appendix B.

RESULTS AND DISCUSSION

Cultivar Yields

The number of days to anthesis for the eleven cultivars grown in Ames can be seen in Table 5. This measurement gives an indication of the relative maturity of the cultivars, although the cultivars did differ in rates of post-anthesis development (data not shown). Considering cultivar maturation aids in the discussion of yield characteristics.

Percent dry matter, dry matter yield, reducing sugar yield, sucrose yield, and total sugar yields for cultivars, years and locations are shown in Table 6. The statistical analysis of these data is shown in Tables 7 to 11. Replicate means were

Table 5. Days to anthesis in eleven cultivars grown in Ames in 1991-1993. The cultivars are ranked according to their mean days to anthesis.

	Production Year			
Cultivar	1991	1992	1993	Mean
Waconia	73	97	80	83
Kansas Orange	73	97	80	83
Smith	80	97	86	88
Sugar Drip	80	113	86	93
Cowley	91	104	106	100
Theis	99	113	92	101
M81E	91	113	109	104
Dale	99	113	109	107
Keller	91	122	106	107
Wray	93	122	106	107
Grassl	96	118	111	108
Mean	88	110	98	

Table 6. Mean values of percent dry matter, dry matter yield, glucose yield, sucrose yield and total sugar yield, for years, locations and cultivars.

Year	Location	Cultivar	% Dry matter	Dry matter	Reducing sugars	Sucrose	Total sugar†
				--------------------Mg ha^{-1}	--------------------		
1991			26.7	14.9	2.6	2.9	5.6
1992			25.4	22.4	3.7	7.2	11.3
1993			23.5	11.5	2.2	2.0	4.2
	AAERC		23.6	18.3	3.4	4.2	7.9
	McMRC		26.3	14.7	2.3	4.0	6.6
1991	AAERC		24.5	15.7	2.9	3.3	6.4
1991	McMRC		27.8	14.5	2.4	2.7	5.3
1992	AAERC		24.0	23.0	4.3	6.6	11.2
1992	McMRC		26.8	21.8	3.1	7.9	11.4
1993	AAERC		22.7	14.9	2.8	2.3	5.3
1993	McMRC		24.2	8.2	1.5	1.6	3.2
		Waconia	23.4	12.4	2.0	2.3	4.4
		Kansas O.	26.6	16.0	2.5	3.4	6.1
		Smith	27.4	15.3	1.6	4.9	6.7
		Sugar D.	24.1	15.8	2.8	4.5	7.4
		Cowley	25.4	16.3	2.4	5.0	7.7
		Theis	26.0	16.7	3.5	3.7	7.4
		M81E	24.0	18.1	3.5	3.5	7.2
		Dale	23.4	15.8	4.3	3.4	7.8
		Keller	24.7	17.9	2.7	5.4	8.3
		Wray	25.0	17.5	2.8	5.0	8.0
		Grassl	25.4	18.2	3.2	4.2	7.6
1991		Waconia	24.5	6.3	0.7	0.4	1.1
1992		Waconia	23.6	19.7	3.0	4.9	8.2
1993		Waconia	22.3	9.7	1.8	1.2	3.1
1991		Kansas O.	28.9	13.2	1.9	1.5	3.5
1992		Kansas O.	26.6	23.6	3.6	6.6	10.6
1993		Kansas O.	24.7	11.3	1.9	2.1	4.1
1991		Smith	28.7	14.7	1.5	4.0	5.7
1992		Smith	28.9	20.7	2.1	7.9	10.4
1993		Smith	24.9	10.3	1.2	2.5	3.9
1991		Sugar D.	25.5	15.0	2.4	3.1	5.6
1992		Sugar D.	24.1	22.3	4.0	8.2	12.5
1993		Sugar D.	22.4	10.7	2.1	2.3	4.5

Table 6. (continued)

Year	Location	Cultivar	% Dry matter	Dry matter	Reducing sugars	Sucrose	Total sugar†
				--------------------Mg ha^{-1}	--------------------		
1991		Cowley	27.7	13.5	2.0	3.7	5.8
1992		Cowley	25.9	22.2	3.0	8.4	11.8
1993		Cowley	23.2	12.5	2.0	2.7	4.8
1991		Theis	27.7	15.7	3.2	2.6	6.0
1992		Theis	25.9	22.0	4.5	6.1	10.9
1993		Theis	24.8	12.1	2.8	2.1	5.0
1991		M81E	24.4	18.2	3.8	2.6	6.6
1992		M81E	23.9	22.3	4.2	6.2	10.7
1993		M81E	23.9	13.9	2.4	1.6	4.1
1991		Dale	25.0	15.5	4.0	2.5	6.6
1992		Dale	23.6	21.4	5.4	6.5	12.2
1993		Dale	22.1	10.6	3.4	0.9	4.4
1991		Keller	26.0	14.7	2.3	3.9	6.4
1992		Keller	25.3	24.7	3.5	9.0	13.0
1993		Keller	23.1	13.5	2.1	2.9	5.1
1991		Wray	26.9	16.1	2.4	4.3	6.9
1992		Wray	24.8	23.8	3.9	8.0	12.3
1993		Wray	23.7	11.6	1.9	2.1	4.1
1991		Grassl	27.1	21.0	4.1	3.3	7.6
1992		Grassl	26.4	23.8	3.7	7.6	11.7
1993		Grassl	23.2	10.5	2.0	1.5	3.6

† Total sugar given in glucose equivalents.

Table 7. Analysis of variance for percent dry matter at AAERC and McMRC for the years 1991-1993.

Source	df	Mean square
Year	2	41.86**
Location	1	107.88**
Year*location	2	4.94
Cultivar	10	9.45**
Year*cultivar	20	1.11
Location*cultivar	10	1.05
Error	20	1.75
Corrected Total	65	
Contrasts:		
Waconia, Kansas O. vs. all	1	0.01
Waconia vs. all	1	17.98**
Dale vs. all	1	16.49**
Smith vs. all	1	29.19**
Dale vs. Smith	1	40.70**
Smith vs. Waconia	1	42.26**
Dale, Theis, M81E vs. all	1	7.10
Grassl, M81E vs. all	1	1.20
Keller, Wray vs. all	1	1.31
M81E, Grassl, Wray vs. Waconia, Smith, Kansas O.	1	7.96*

*,** indicate significance at the .05 and .01 levels respectively

Table 8. Analysis of variance for dry matter yield at AAERC and McMRC for the years 1991-1993.

Source	df	Mean square
Year	2	667.88**
Location	1	154.87**
Year*location	2	56.72**
Cultivar	10	19.54**
Year*cultivar	20	7.56*
Location*cultivar	10	3.83
Error	20	3.29
Corrected total	65	
Contrasts:		
Waconia, Kansas O. vs. all	1	70.92**
Waconia vs. all	1	125.74**
Dale vs. all	1	1.70
Smith vs. all	1	12.11
Dale vs. Smith	1	2.15
Smith vs. Waconia	1	27.18**
Dale, Theis, M81E v. all	1	9.30
Grassl, M81E vs. all	1	63.66**
Keller, Wray vs. all	1	17.01*
M81E, Grassl, Wray vs. Waconia, Smith, Kansas O.	1	117.623**

*,** indicate significance at the .05 and .01 levels respectively

Table 9. Analysis of variance for reducing sugar yield at AAERC and McMRC for the years 1991-1993.

Source	df	Mean square
Year	2	13.62**
Location	1	16.37**
Year*location	2	0.95*
Cultivar	10	3.53**
Year*cultivar	20	0.44*
Location*cultivar	10	0.13
Error	20	0.17
Corrected total	65	
Contrasts:		
Waconia, Kansas O. vs. all	1	5.95**
Waconia vs. all	1	6.20**
Dale vs. all	1	13.35**
Smith vs. all	1	9.79**
Dale vs. Smith	1	20.91**
Smith vs. Waconia	1	0.19
Dale, Theis, M81E vs. all	1	20.58**
Grassl, M81E vs. all	1	5.01**
Keller, Wray vs. all	1	0.23
M81E, Grassl, Wray vs. Waconia, Smith, Kansas O.	1	12.94**

*,** indicate significance at the .05 and .01 levels respectively

Table 10. Analysis of variance for sucrose yield at AAERC and McMRC for the years 1991-1993.

Source	df	Mean square
Year	2	170.51**
Location	1	0.01
Year*location	2	7.23**
Cultivar	10	4.72**
Year*cultivar	20	0.66
Location*cultivar	10	0.42
Error	20	0.50
Corrected total	65	
Contrasts:		
Waconia, Kansas O. vs. all	1	20.98**
Waconia vs. all	1	22.55**
Dale vs. all	1	3.64*
Smith vs. all	1	2.85*
Dale Vs. Smith	1	5.87**
Smith vs. Waconia	1	18.83**
Dale, Theis, M81E vs. all	1	6.88**
Grassl, M81E vs. all	1	0.65
Keller, Wray vs. all	1	12.78**
M81E, Grassl, Wray vs. Waconia, Smith, Kansas O.	1	4.19**

*,** indicate significance at the .05 and .01 levels respectively

Table 11. Analysis of variance for total sugar yield at AAERC and McMRC for the years 1991-1993.

Source	df	Mean square
Year	2	301.60**
Location	1	15.69**
Year*location	2	7.11**
Cultivar	10	7.41**
Year*cultivar	20	1.63
Location*cultivar	10	0.88
Error	20	0.93
Corrected total	65	
Contrasts:		
Waconia, Kansas O. vs. all	1	52.57**
Waconia vs. all	1	55.86**
Dale vs. all	1	2.73
Smith vs. all	1	1.85
Dale vs Smith	1	4.12*
Smith vs. Waconia	1	16.99**
Dale, Theis, M81E vs. all	1	3.17
Grassl, M81E vs. all	1	1.95
Keller, Wray vs. all	1	10.70**
M81E, Grassl, Wray vs Waconia, Smith Kansas O.	1	33.04**

*,** indicate significance at the .05 and .01 levels respectively

used. The cultivar Smith had the highest percent dry mater at harvest, whereas Grassl yielded the most dry matter over all years and locations. The yield characteristics showed differences among locations, years and cultivars. Whereas the cultivars performed consistently at each location, there were cultivar by year differences and location by year differences. This result is explained by the major differences in site fertility, difference in latitude, and climatic differences in years.

Several queries explain the cultivar differences in more detail (Tables 7 to 11). The two early-maturing cultivars, Waconia and Kansas Orange, accounted for a large amount of the low dry matter yield capacity of the cultivars, and Waconia alone even to a larger extent. The late-maturing cultivars, M81E, Grassl, and Wray stand out significantly from all others as high-yielding cultivars. This trend shows even greater significance when they are contrasted with the three early cultivars, Waconia, Smith and Kansas Orange.

Often percent dry matter is considered a measure of maturity. Differences in percent dry matter were seen between the early cultivar Smith and all other cultivars, yet also between Smith and Waconia, another early cultivar. Smith had the highest percent dry matter and Waconia the lowest. Significantly lower dry matter percentages between the late cultivars and all others were not elucidated. The incongruencies exhibited by Smith and Waconia may be due to the fact that while Waconia has been used as a sugar crop, it was also developed for use as a forage. Thus, it is characterized by a leafier, stemier, more "stay-green" habit than Smith. In this study , percent dry matter did not agree with other maturity characteristics (Table 5). It is notable that there have been previous discrepancies in the relative maturities of cultivars by study site. For example, Smith was described as a late-maturing cultivar when released in Texas (Kresovich and Broadhead, 1988) but when grown here, at more northern latitudes, it was among the early cultivars. Also, Wray was described as 1.4 m shorter than Grassl when grown in central California (Hills et al., 1990). When grown in Iowa, the two cultivars were similar in height. These discrepancies may be due to the fact that there are differences among cultivars in their sensitivity to temperature and photoperiod and that the thermal requirements of a cultivar must be met before a photoperiod response (and reproductive growth) is initiated (Coleman and Belcher, 1952).

While Dale produced the most reducing sugar (presented in Table 6 as glucose equivalents), Keller accumulated more sucrose by harvest and, in turn, more total sugar (presented as glucose equivalents) than the other cultivars. As noted above, sucrose yields are often correlated with total sugar yields. Cultivar treatment differences in the sugar yield characteristics were less clear. Reducing sugar, sucrose and total sugar production exhibited year by location interaction. Within this, reducing sugar production differed by location, yet sucrose yields were not significantly different by location. This discrepancy was lost when total sugar yield was considered. Due to the differences in these three categories of sugar each year, the interactive effect of year and location was significant. In 1992, more sucrose was produced by the cultivars in southern Iowa (the inverse being true in the other two years), and the total sugar values were almost equal at the two locations. It may be wise to be conservative when evaluating differences in reducing sugar and sucrose production due to the change made in sample preservation prior to sugar analysis (between 1992 and 1993). However, the trends in reducing sugar and sucrose production over all years appear to be consistent.

Cultivar distinction in sugar production warrant further consideration. Once again, Waconia and Kansas Orange yielded substantially less in all three sugar categories, Waconia even more so when considered alone. Dale, a mid to late-season cultivar, stood apart with the highest reducing sugar yield. Alternately, reducing sugar made up proportionately less of the soluble carbohydrate yield for Smith, an early cultivar, than any other cultivar. As expected, this relationship held significantly when Dale and Smith are compared. Ventre et al. (1939) also noted differences between cultivars in the ratio of sucrose to reducing sugars. Smith differed significantly from Waconia in sucrose and total sugar yield. These differences may correspond to the possible anomalies in percent dry matter mentioned above, when considering these two early cultivars. In general, sucrose values are expected to increase and reducing sugar values to decrease as the plant matures and becomes reproductive (Lingle, 1987). However, as mentioned above, forage traits have been emphasized in the improvement of Waconia (Kalton, 1988). A heavy panicle is produced, and probably proportionately more photosynthate is allocated for grain production and less for storage in the stalk to improve its overall forage nutritive value.

The three more recently developed cultivars, Dale, M81E and Theis, differed significantly from the others in reducing sugar production. When the two latest and highest dry matter yielding cultivars, M81E and Grassl, were compared to the others, their glucose yields are significantly higher. Keller and Wray, a mid to late-season cultivar and late cultivar respectively, had significantly higher sucrose and total sugar yields when compared to all other cultivars. Finally, in a comparison of the three latest cultivars, Grassl, M81E and Wray, with the three earliest, Waconia, Kansas Orange and Smith, glucose and total sugar yields are significantly higher in the former group.

Several overall yield differences deserve discussion. Although percent dry matter was highest in 1991 and lowest in 1993, dry matter yields were highest in 1992 and lowest in 1993. A general summary would be as follows: conditions in 1992 were favorable for long periods of growth per stage and/or the initiation and production of many plant units, i.e. more potential for dry matter production. Alternately, conditions in 1991 hastened plant maturity (increased the final percent dry matter) thereby decreasing dry matter production, relative to 1992. This pattern also is illuminated in the number of days to anthesis per year (Table 5). In 1992, the plants at Ames also produced more tillers than in the other years (Appendix B). The cool and wet conditions of 1993 had deleterious effects on plant growth and maturation as well as increased the possibility of pathogen invasion.

A similar case can be made for differences in percent dry matter and yield at the two locations. In southern Iowa, the plants experience shorter days before those in Ames, receive more temperature units, and therefore are slightly advanced in maturity, the exception being 1993. Coleman and Belcher (1952) described a positive correlation between daylength and plant height and a negative correlation between warm temperatures and plant height (i.e. a short growing period). They also found that the average daily temperatures for 30 d after planting and the number of days from planting to anthesis were negatively correlated.

If the general differences in maturation in this study are consistent, one might expect that sucrose, the predominant form of storage carbohydrate in mature sweet sorghum stalk tissue, to be relatively higher at the southern location. In fact, as stated above, sucrose production does not appear to be influenced by location. At the time of harvest, the cultivars produced the same amount of sucrose over 3 yr. This was possibly due to the fact that the plants in southern Iowa were more mature and in Ames because the growth period was longer and more total dry matter accumulated. As stated above, this parity is lost when total sugar is considered. It should be noted, however, that in 1992 and 1993, sucrose concentrations were higher and reducing sugar concentrations were lower McMRC than at AAERC (data not shown).

It should also be noted that stand establishment was poor in 1992 and 1993 due to poor germination (Appendix B). Therefore the yield overestimations associated with plot work were probably more pronounced. Also, the space-filling nature of sweet sorghum plants allows for oversights in accounting for yield losses due to row gaps.

Brix Readings

In the periodic measurement of Brix (percent soluble carbohydrate) values for the cultivars grown at Ames, all effects were significant in all years except cultivars were not different by date in 1993 and the readings taken at Internodes 4 and 8 were not significantly different in 1993 (Tables 12 to 15). Differences between 6 cultivars for each year can be seen in Figures 1 to 3. Regressions of brix value means on days for each year are shown in Figures 4a to 4c. Although a linear equation describes the average sugar production of the cultivars well, the early cultivars (such as Waconia and Smith) might be better described by a quadratic function (Figures 1 to 3). When considering the anthesis dates of the cultivars represented in these figures, the date appeared to precede a peak and then a decline in sugar concentration for Waconia in all years, and for all cultivars in 1992.

Also of note are differences between internode Brix values by date within years (Table 16). Each year shows a transition between values being higher in the lower internode at early dates, to being higher in the upper internode at later dates. This relationship is depicted in Figures 5 to 7, where three early cultivars,

Table 12. Brix readings taken at AAERC on eleven cultivars for three years.

		Cultivar										
Year	Date	Waconia	Kansas Orange	Smith	Sugar Drip	Cowley	Theis	M81E	Dale	Keller	Wray	Grassl
1991	14 Aug	5.5	6.6	5.8	6.0	5.0	4.4	4.1	5.0	4.5	4.8	4.5
1991	21 Aug	7.8	9.8	7.8	7.3	6.4	5.1	4.7	6.1	5.7	5.7	4.9
1991	28 Aug	9.5	13.6	10.1	10.0	9.2	7.7	6.1	7.4	7.9	7.6	7.2
1991	8 Sep	8.1	13.3	13.6	12.6	13.0	10.4	9.2	10.9	10.0	10.8	10.3
1992	14 Aug	5.5	6.4	7.3	-	-	-	-	-	-	-	-
1992	22 Aug	9.0	10.7	11.9	-	9.1	-	-	-	-	-	-
1992	29 Aug	10.7	11.9	14.2	9.7	11.3	9.5	6.2	8.0	7.7	-	-
1992	4 Sep	12.4	13.2	16.2	11.2	12.7	10.0	7.7	9.7	9.4	11.0	11.7
1992	11 Sep	12.4	13.7	14.2	12.3	15.3	11.2	9.4	9.9	10.9	12.1	13.4
1992	21 Sep	11.6	13.6	13.5	13.8	14.4	11.9	9.3	12.3	12.7	12.7	13.1
1993	16 Aug	3.8	-	-	-	-	-	-	-	-	-	-
1993	23 Aug	5.1	7.1	6.2	-	-	-	-	-	-	-	-
1993	30 Aug	5.5	8.3	6.7	6.7	5.7	6.0	5.3	5.8	6.4	-	-
1993	5 Sep	7.4	12.1	10.4	8.4	8.1	8.6	6.3	7.5	9.1	8.5	-
1993	16 Sep	12.2	15.1	12.1	11.4	10.3	11.2	8.2	8.7	10.8	10.9	10.9
1993	25 Sep	12.1	15.0	14.5	13.7	14.2	12.4	11.3	11.9	14.2	13.3	12.1

Table 13. Analysis of variance for Brix readings taken at AAERC in 1991.

Source	df	Mean square
Blocks	2	30.96*
Cultivar	10	93.05**
Error a	20	7.42
Date	3	913.40**
Cultivar*date	30	10.36**
Error b	66	2.16
Internode	1	24.79**
Cultivar*internode	10	5.73**
Date*internode	3	62.49**
Cultivar*date*internode	30	1.58*
Error c	352	0.99
Corrected total	527	
Contrast:		
Early vs. late	1	496.13**

*,** indicate significance at the .05 and .01 levels respectively

Table 14. Analysis of variance for Brix readings taken at AAERC in 1992.

Source	df	Mean square
Blocks	1	155.57*
Cultivar	10	112.23**
Error a	10	19.72
Date	5	277.46**
Cultivar*date	34	6.16*
Error b	39	2.96
Internode	1	41.73**
Cultivar*internode	10	12.84**
Date*internode	5	28.19**
Cultivar*date*internode	34	2.47**
Error c	250	1.42
Corrected total	399	
Contrast:		
Early vs. late	1	185.41*

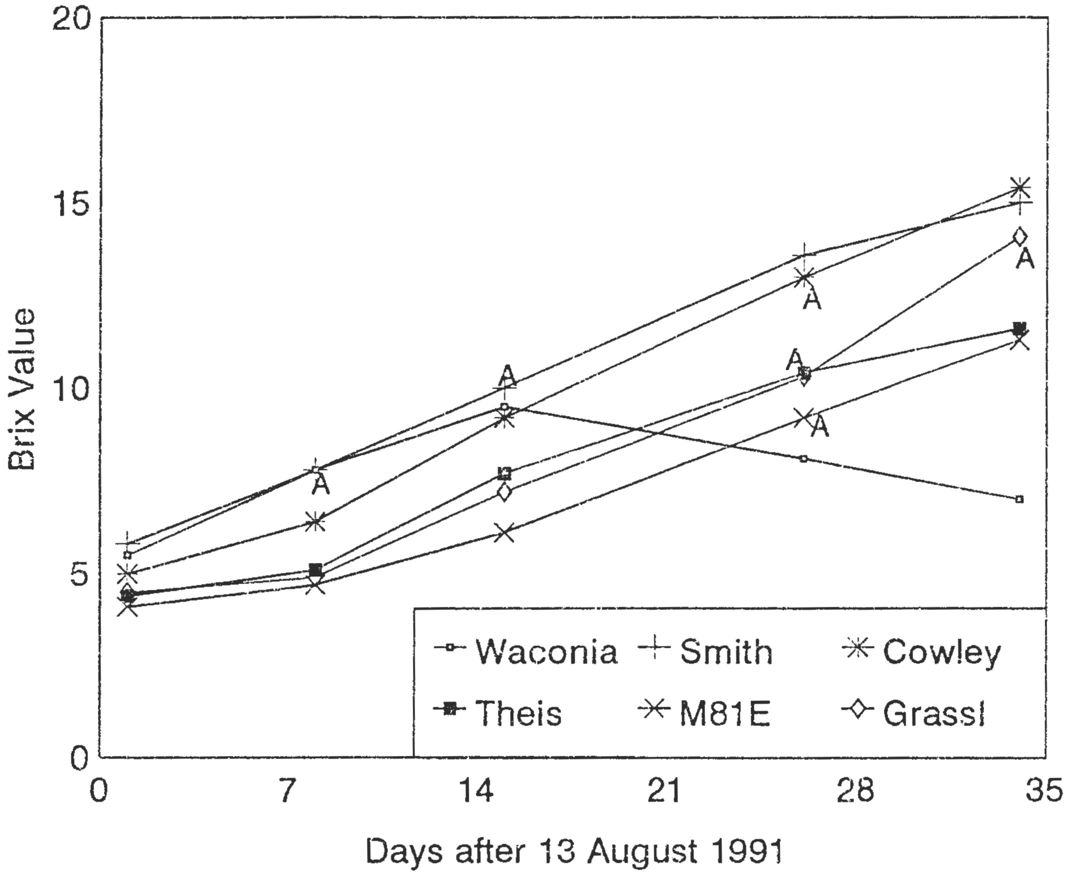
*,** indicate significance at the .05 and .01 levels respectively

Table 15. Analysis of variance for Brix readings taken at AAERC in 1993.

Source	df	Mean Square
Blocks	1	4.95
Cultivar	10	40.15**
Error a	10	2.15
Date	5	498.95**
Cultivar*date	29	3.14
Error b	23	3.69**
Internode	1	0.87
Cultivar*internode	10	9.13**
Date*internode	5	10.28**
Cultivar*date*internode	29	0.89
Error c	192	1.33
Corrected total	315	
Contrast:		
Early vs. late	1	0.00†

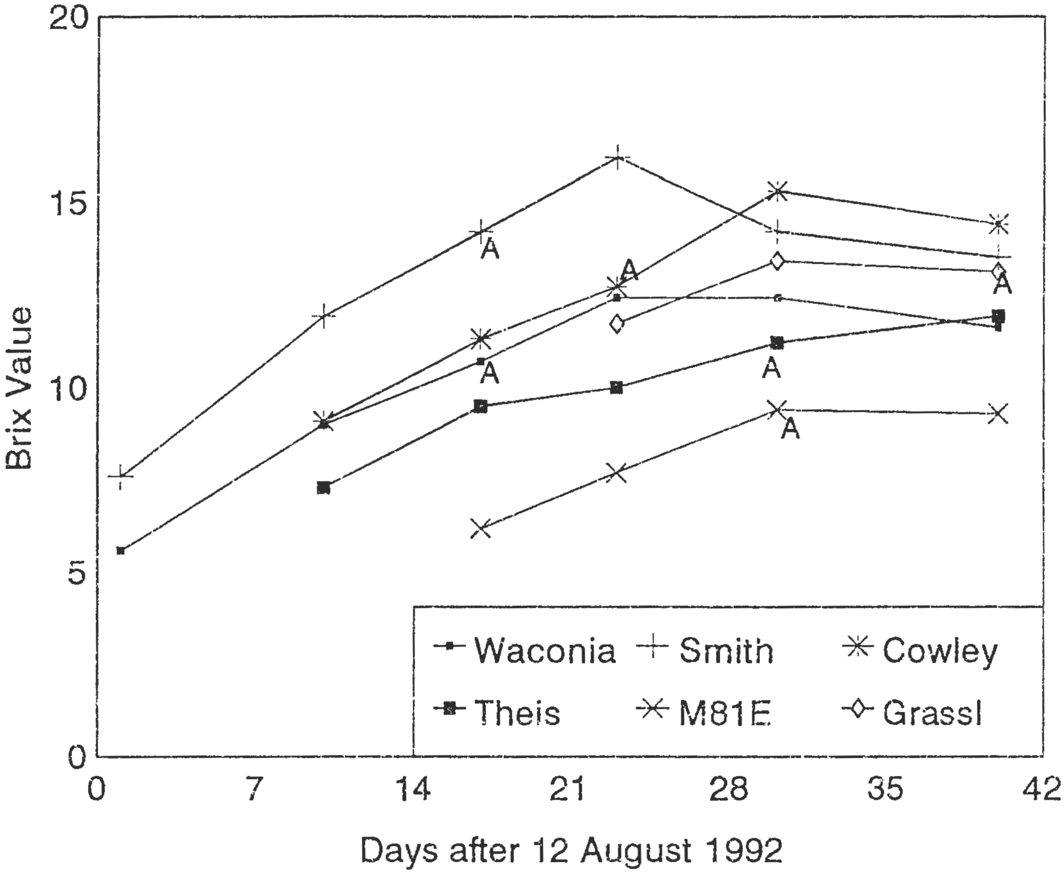
*,** indicate significance at the .05 and .01 levels respectively

† due to the unbalanced nature of this mean comparison, a t-test was calculated and was not significant.



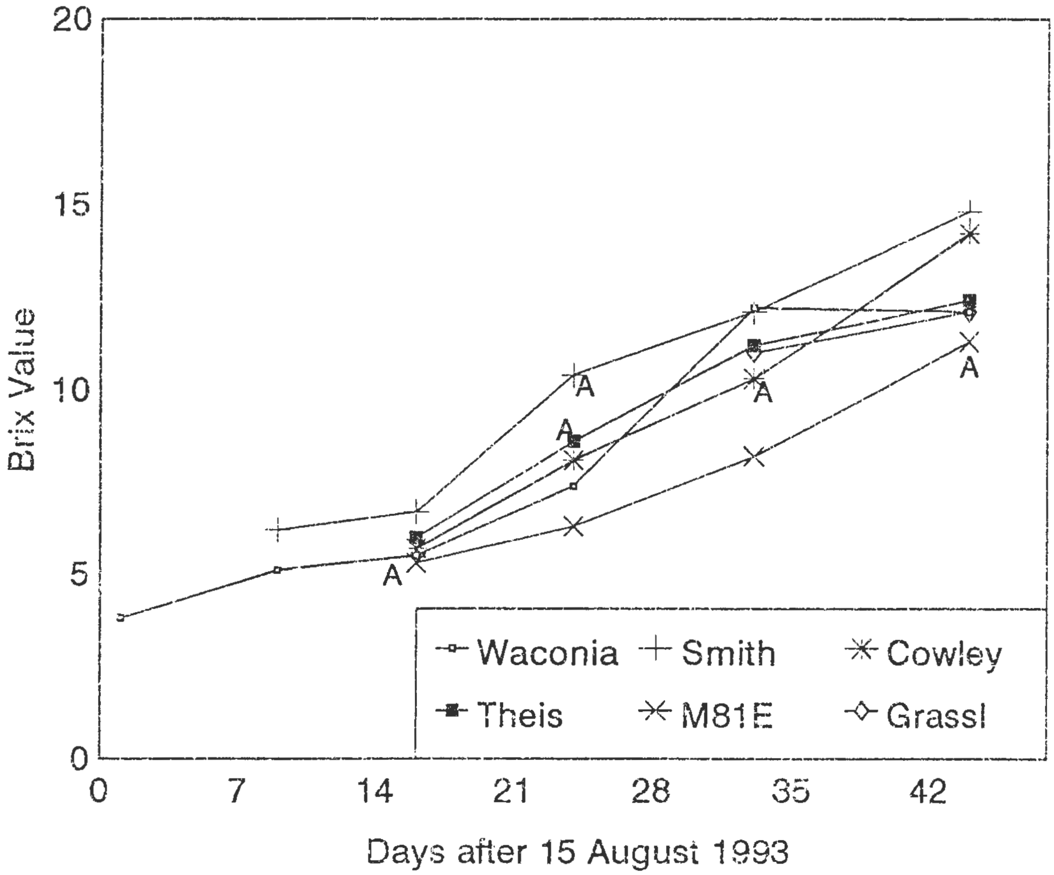
$Lsd_{.05}$ between dates within a cultivar= 1.7

Figure 1. Brix values for six cultivars over five dates in 1991 at AAERC. The fifth date is a mean of two readings only and was not included in the statistical analysis. The symbol A on the figure represents the date of anthesis.



Lsd$_{.05}$ between dates within a cultivar= 2.5

Figure 2. Brix values for six cultivars over six dates in 1992 at AAERC. The symbol A on the figure represents the date of anthesis.



$Lsd_{.05}$ between dates within a cultivar= 2.7

Figure 3. Brix values for six cultivars over six dates in 1993 at AAERC. The symbol A on the figure represents the date of anthesis.

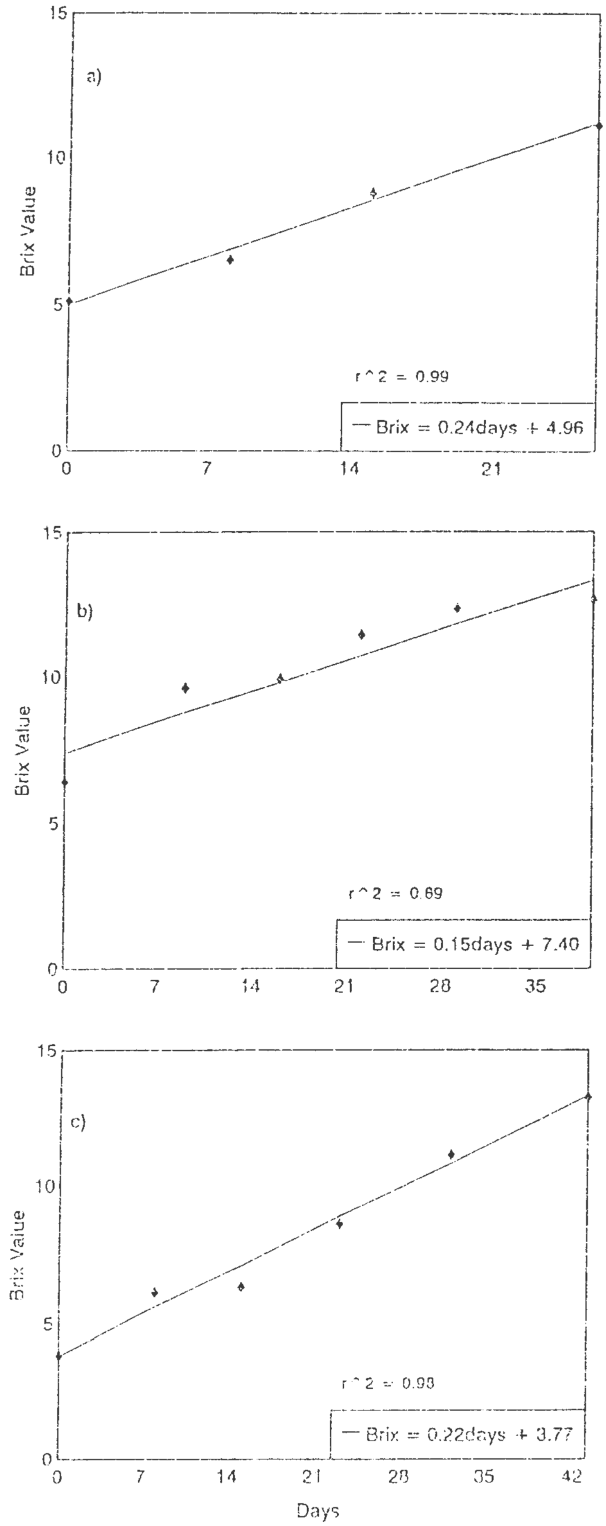
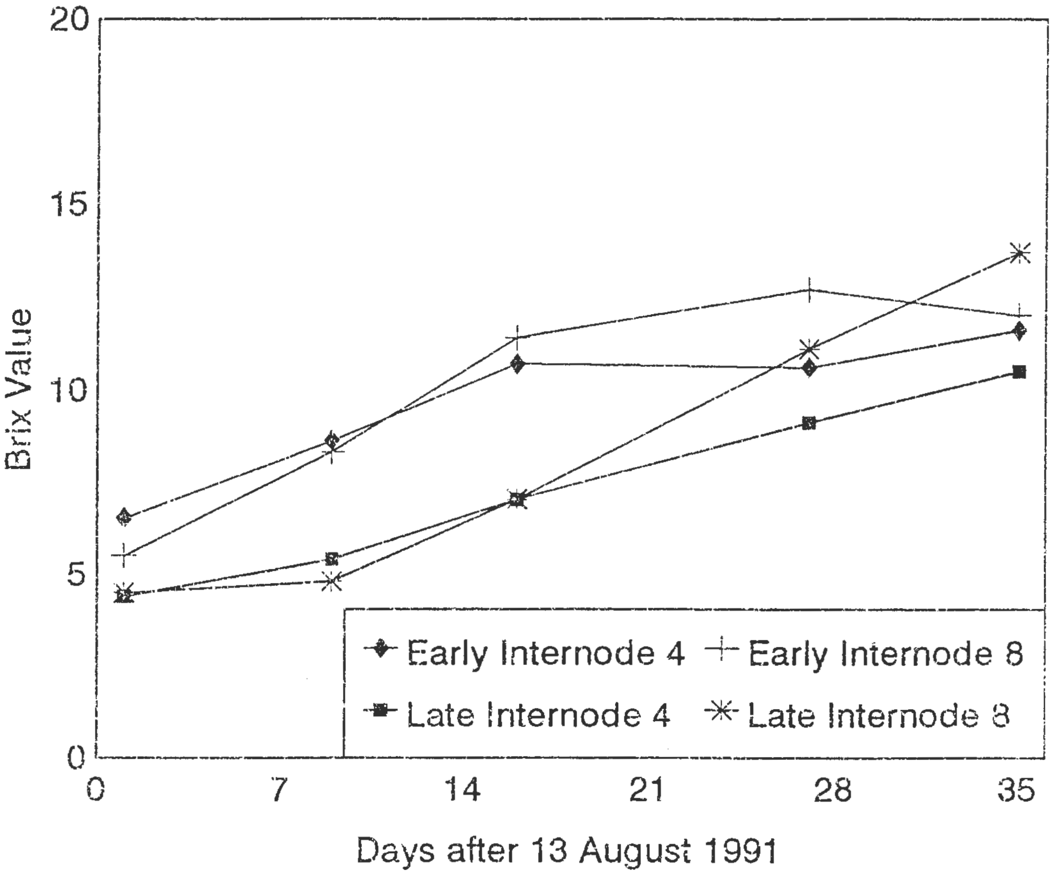


Figure 4. Linear regression of Brix values on days for cultivars grown at AAERC in a) 1991, b) 1992, and c) 1993.

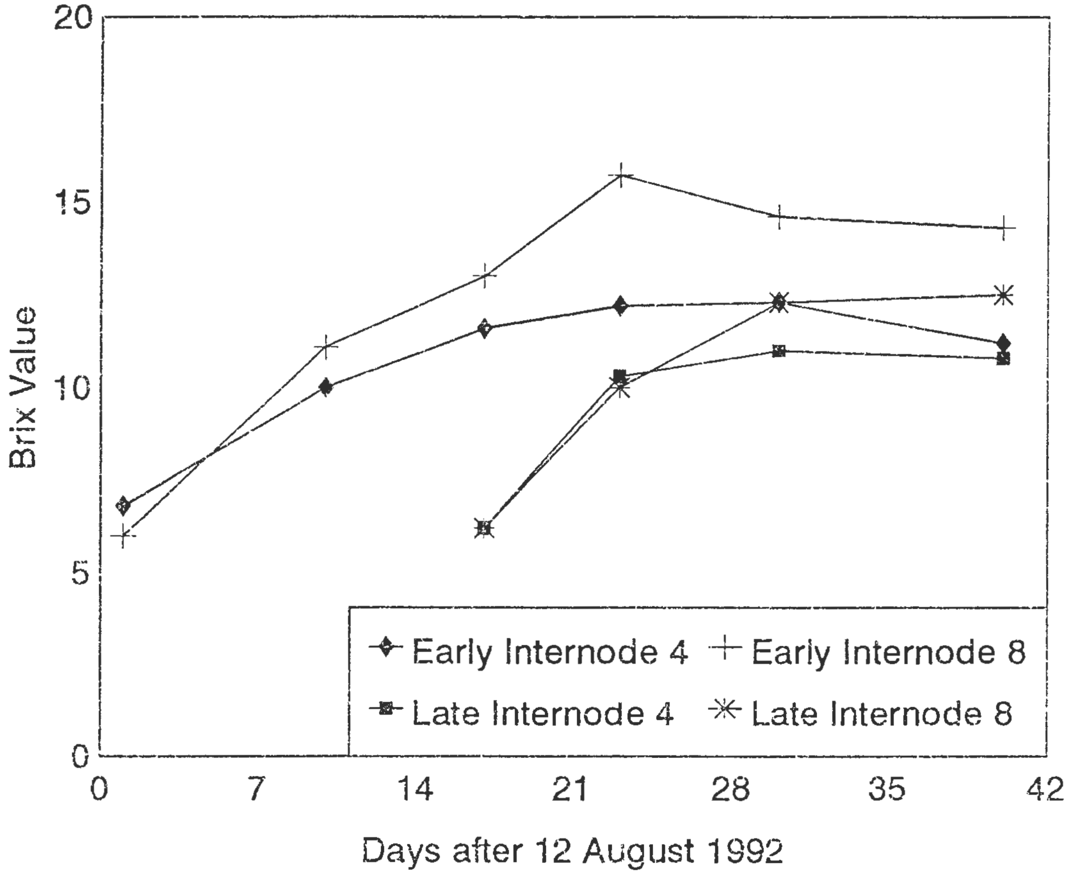
Table 16. Brix reading means for Internodes 4 and 8 for all cultivars and years at AAERC.

Year	Date	Internode 4	Internode 8
		------------------Brix value	-------------------
1991	14 Aug	5.4	4.9
1991	21 Aug	6.8	6.1
1991	28 Aug	8.6	9.0
1991	8 Sep	10.0	12.4
1992	14 Aug	6.9	6.0
1992	22 Aug	9.6	9.8
1992	29 Aug	10.0	10.3
1992	4 Sep	10.8	12.2
1992	11 Sep	11.4	13.3
1992	21 Sep	11.4	14.1
1993	16 Aug	4.0	4.0
1993	23 Aug	6.3	5.7
1993	30 Aug	6.4	6.1
1993	5 Sep	8.4	8.9
1993	16 Sep	10.7	11.3
1993	25 Sep	12.3	13.7



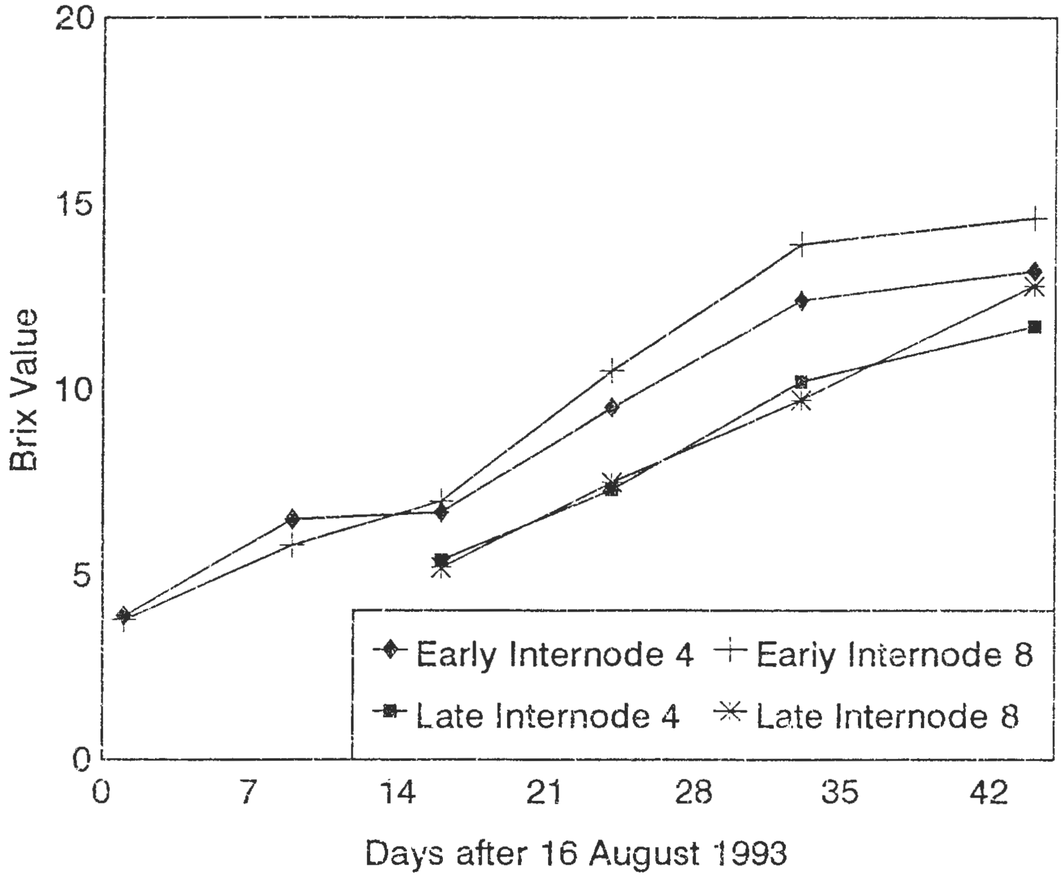
Lsd$_{.05}$ for internode comparison within a cultivar group and date= 1.3

Figure 5. Brix values at internodes four and eight of three early cultivars compared with three late cultivars over five dates in 1991 at AAERC. The fifth date is a mean of two readings only and was not included in the statistical analysis.



$Lsd_{.05}$ for internode comparison within a cultivar group and date= 2.3

Figure 6. Brix values at internodes four and eight of three early cultivars compared with three late cultivars over six dates in 1992 at AAERC.



Lsd$_{.05}$ for internode comparison within a cultivar group and date= 2.3

Figure 7. Brix values at internodes four and eight of three early cultivars compared with three late cultivars over six dates in 1993 at AAERC.

Waconia, Kansas Orange, and Smith, and three late cultivars, M81E, Grassl, and Wray, are compared. The 1991 and 1992 results show an abrupt transition. In 1993, at several mid-season dates the upper and lower internodes had approximately equal values before the high and low values were reversed. Finally, the difference in Brix readings at later dates was greater in 1991 and 1992 than in 1993. The average Brix readings of the three early cultivars and of the three late cultivars shown in Figures 5 to 7 were different only in 1991 and 1992 (Tables 13 to 15).

This transition in sugar distribution in the plant can be attributed to sink-source changes within the plant. In younger plants, the lower internodes completed their growth and became net store of carbohydrate, whereas the upper internodes continued to elongate and expend resources in laying down new tissue. As the successional elongation of internodes slows and stops (with the onset of panicle growth), all internodes are potentially storing carbohydrate or exporting it to the panicle. However, it was speculated (McBee et al., 1983) that the panicle receives an excess of stored and new carbohydrate and is itself an exporter well into the reproductive phase. There does not seem to be consensus as to when this period ends; the panicle becomes a sink sometime during early seed formation. Therefore, the upper internodes, being proximal to the panicle, are closer to a sugar source and have a larger pool of sugar later in the season. This relationship is more transient in individual cultivars, on a yearly basis. Overall means for both internodes were the highest in 1992, followed by 1993 and 1991.

Morphological Measurements

Number of mature leaves, number of visible nodes and plant height were measured in the eleven cultivars at five dates in 1992 and six dates in 1993 at Ames. Means of all three variables were different by date in both years, but only node number and plant height were different by cultivar in both years (Tables 17 to 22). This is a curious result considering the fact that highly significant positive correlations between number of leaves and plant height have been observed (Coleman and Belcher, 1952). The number of leaves produced has also been shown to be correlated with number of days to anthesis (Coleman and Belcher, 1952). Cultivars differed in days to anthesis in this study (Table 5); thus, a difference in leaf production would be expected. Plant height might be expected to be influenced by the number of nodes seen, or internodes produced. However, as discussed above, total plant height also was influenced by the amount of time spent in each growth stage, i.e. how long of a period an internode developed before growth terminated. Differences in leaf production may have been elucidated if the sampling period had begun earlier in the season when plant growth was dominated by leaf production. More specific cultivar leaf growth differences may also have been noted if leaf area had been measured.

Mean leaf counts, visible node counts, and plant height measurements for the cultivars at a mid-september date for 1992 and 1992 were compared (Table 23). All three variables showed significant differences among cultivars and years (Tables 24 to 26). The totals were all greater in 1992. Since 1992 was also the

Table 17. Analysis of variance for number of leaves produced by eleven cultivars at five dates at AAERC in 1992.

Source	df	Mean square
Block	1	0.3
Cultivar	10	24.8
Error a	10	9.7
Date	4	930.6**
Cultivar*date	40	9.3**
Error b	44	0.3
Corrected total	113	

*,** indicate significance at the .05 and .01 levels respectively

Table 18. Analysis of variance for number of nodes produced by eleven cultivars at five dates at AAERC in 1992.

Source	df	Mean square
Block	1	0.3
Cultivar	10	39.9**
Error a	10	1.4
Date	4	1472.1**
Cultivar*date	40	6.2**
Error b	44	0.5
Corrected total	113	

*,** indicate significance at the .05 and .01 levels respectively

Table 19. Analysis of variance for plant height in eleven cultivars at five dates at AAERC in 1992.

Source	df	Mean square
Block	1	127
Cultivar	10	14029**
Error a	10	2203
Date	4	1115035**
Cultivar*date	40	3259**
Error b	44	408
Corrected total	113	

*,** indicate significance at the .05 and .01 levels respectively

Table 20. Analysis of variance for number of leaves produced by eleven cultivars at six dates at AAERC in 1993.

Source	df	Mean square
Block	1	17.7
Cultivar	10	17.8
Error a	10	7.3
Date	5	1362.8**
Cultivar*date	50	8.4**
Error b	55	0.6
Corrected total	131	

*,** indicate significance at the .05 and .01 levels respectively

Table 21. Analysis of variance for number of nodes produced by eleven cultivars at six dated in 1993.

Source	df	Mean square
Block	1	16.8
Cultivar	10	42.5*
Error a	10	11.3
Date	5	1130.4**
Cultivar*date	50	6.6**
Error b	55	1.5
Corrected total	131	

*,** indicate significance at the .05 and .01 levels respectively

Table 22. Analysis of variance for plant height in eleven cultivars at six dates at AAERC in 1993.

Source	df	Mean square
Block	1	23975
Cultivar	10	24430*
Error a	10	7118
Date	5	935353**
Cultivar*date	50	3422**
Error b	55	541
Corrected total	131	

*,** indicate significance at the .05 and .01 levels respectively

Table 23. Leaf number, visible node number and plant height means in mid-September for eleven cultivars at AAERC in 1992 and 1993.

Year	Cultivar	Leaves	Nodes	Height
				---M---
1992	Waconia	20.3	12.8	3.0
1992	Kansas O.	19.0	12.6	3.6
1992	Smith	18.8	12.1	3.5
1992	Sugar D.	20.5	11.3	3.4
1992	Cowley	20.3	12.9	3.5
1992	Theis	21.8	13.8	3.9
1992	M81E	22.0	13.4	3.8
1992	Dale	20.3	12.6	3.9
1992	Keller	21.8	14.5	3.9
1992	Wray	21.0	14.1	3.8
1992	Grassl	20.8	13.0	3.6
1992	Mean	20.6	13.0	3.6
1993	Waconia	16.4	10.4	2.1
1993	Kansas O.	16.7	10.8	2.6
1993	Smith	17.1	11.0	2.8
1993	Sugar D.	17.1	9.9	2.6
1993	Cowley	18.0	9.9	2.4
1993	Theis	18.4	12.0	2.9
1993	M81E	18.8	10.8	2.6
1993	Dale	17.2	10.7	2.8
1993	Keller	18.7	10.9	2.9
1993	Wray	17.9	11.1	3.1
1993	Grassl	15.2	8.7	2.2
1993	Mean	17.4	10.6	2.6

Table 24. Analysis of variance for number of leaves produced by eleven cultivars by mid-September at AAERC in 1992 and 1993.

Source	df	Mean square
Block	1	0.92
Cultivar	10	20.47**
Error a	10	1.68
Year	1	448.81**
Year*cultivar	10	2.20
Error b	182	1.23
Corrected total	214	

*,** indicate significance at the .05 and .01 levels respectively

Table 25. Analysis of variance for number of visible nodes produced by eleven cultivars by mid-September at AAERC in 1992 and 1993.

Source	df	Mean square
Block	1	3.45
Cultivar	10	12.50**
Error a	10	2.26
Year	1	323.89**
Year*cultivar	10	2.89**
Error b	182	0.91
Corrected total	214	

*,** indicate significance at the .05 and .01 levels respectively

Table 26. Analysis of variance for plant height of eleven cultivars by mid-September at AAERC in 1992 and 1993.

Source	df	Mean square
Block	1	4261
Cultivar	10	16928**
Error a	10	1610
Year	1	549676**
Year*cultivar	10	422
Error b	182	556
Corrected total	214	

*,** indicate significance at the .05 and .01 levels respectively

year with the highest yields, these yields could be correlated with the higher number of phytomeric units produced. The specific microclimate present at the time of initiation of those units in 1992 must have been favorable. Perhaps a mechanism similar to the one proposed by Tollenaar and Hunter (1983) for determining the number of leaves produced by maize exists for sweet sorghum. In their experiment the effects of photoperiod and temperature on leaf number were additive. The number of leaf initials that were initiated was sensitive to photoperiod and temperature in the second half of the vegetative phase, or between the four- and seven-leaf stage for maize (Tollenaar and Hunter, 1983).

The rates of change per day in leaf number, visible number of nodes, and plant height were compared over five and six sampling intervals for 1992 and 1993 respectively (Table 27). These slopes differed by cultivar and year and the

Table 27. The means for the rates of change per day for number of leaves, number of visible nodes and plant height for eleven cultivars in two years at AAERC in 1992 and 1993.

Year	Cultivar	Leaves	R-square	Nodes	R-square	Height --mm--	R-square
1992	Waconia	0.09	0.62	0.14	0.75	34	0.88*
1992	Kansas O.	0.09	0.69	0.13	0.81	44	0.92*
1992	Smith	0.09	0.67	0.15	0.78	48	0.93*
1992	Sugar D.	0.16	0.93*	0.19	0.91*	53	0.99**
1992	Cowley	0.16	0.78	0.20	0.91*	55	0.95*
1992	Theis	0.15	0.82	0.20	0.90*	56	0.95*
1992	M81E	0.19	0.94*	0.23	0.96**	61	0.99**
1992	Dale	0.15	0.91*	0.19	0.93*	59	0.99**
1992	Keller	0.19	0.96**	0.23	0.98**	61	0.99**
1992	Wray	0.19	0.97**	0.22	0.99**	60	0.99**
1992	Grassl	0.19	0.96**	0.24	0.97**	59	0.99**
1992	Mean	0.15		0.19		54	
1993	Waconia	0.07	0.39	0.13	0.65	20	0.64
1993	Kansas O.	0.10	0.62	0.15	0.71	30	0.72
1993	Smith	0.11	0.68	0.16	0.76	33	0.79
1993	Sugar D.	0.08	0.68	0.15	0.84*	28	0.85*
1993	Cowley	0.12	0.82*	0.17	0.89*	34	0.91*
1993	Theis	0.12	0.76	0.19	0.88*	38	0.88*
1993	M81E	0.15	0.89*	0.19	0.94**	38	0.91*
1993	Dale	0.10	0.75	0.18	0.88*	37	0.86*
1993	Keller	0.14	0.83*	0.20	0.90*	42	0.90*
1993	Wray	0.13	0.75	0.19	0.86*	41	0.89*
1993	Grassl	0.16	0.99**	0.15	0.96**	34	0.89*
1993	Mean	0.12		0.17		34	

*,** indicate significance at the .05 and .01 levels, respectively

cultivars responded differently in 1992 than in 1993 (Tables 28 to 30). The cultivars with the best and the poorest fit by a linear function are shown for 1993 (Figures 8a to 9c). A full season cultivar, such as Grassl, was often still immature and growing at a significant rate at harvest and therefore was described well by a linear growth model. An early maturing cultivar would tend to have a decline and arrest in growth rate and therefore its growth is not described as accurately. Once again, Waconia showed distinction in growth rates. Its growth curves are more quadratic in nature. This would indicate a decline in CER or carbon gain which corroborates the significantly lower yields seen in Waconia. On the other hand, the full season cultivars would be expected to have more constant CER's; this was reflected in their higher yields. Sweet sorghum cultivars that produce large amounts of biomass have been shown to be more or less photoperiod sensitive; growing them in long daylengths enhances their yields by increasing the vegetative growth period (Miller and McBee, 1993).

Ethanol Production and Potential

Yield components (lactic acid, acetic acid, ethanol and residual sugar) of the cultivar silage for three years are shown in Table 31. All silage components differed by years, whereas only sugar and ethanol yields showed cultivar differences (Tables 32 to 35). Ethanol production was highest in 1992 and lowest in 1991. Sugar residues were significantly higher in 1993 than 1991 or 1992. Given this, and the fact that 1991 silage samples were in storage for a long period of time, it can be assumed that some of the ethanol was lost due to sample

Table 28. Analysis of variance for the rate of change per day in leaf number in eleven cultivars at AAERC in 1992 and 1993.

Source	df	Mean square (x 10^3)
Block	1	0.8
Cultivar	10	27.8**
Error a	10	1.0
Year	1	195.5**
Year*cultivar	10	6.3**
Error b	187	0.7
Corrected total	219	

*,** indicate significance at the .05 and .01 levels respectively

Table 29. Analysis of variance for the rate of change per day in node number in eleven cultivars at AAERC in 1992 and 1993.

Source	df	Mean square (x 10^3)
Block	1	0.3
Cultivar	10	14.6**
Error a	10	1.3
Year	1	501.9**
Year*cultivar	10	5.4**
Error b	187	1.3
Corrected total	219	

*,** indicate significance at the .05 and .01 levels respectively

Table 30. Analysis of variance for the rate of change per day in plant height in eleven cultivars at AAERC in 1992 and 1993.

Source	df	Mean square
Block	1	3.65**
Cultivar	10	13.40**
Error a	10	0.31
Year	1	3.41**
Year*cultivar	10	1.83**
Error b	187	0.50
Corrected total	219	

*,** indicate significance at the .05 and .01 levels respectively

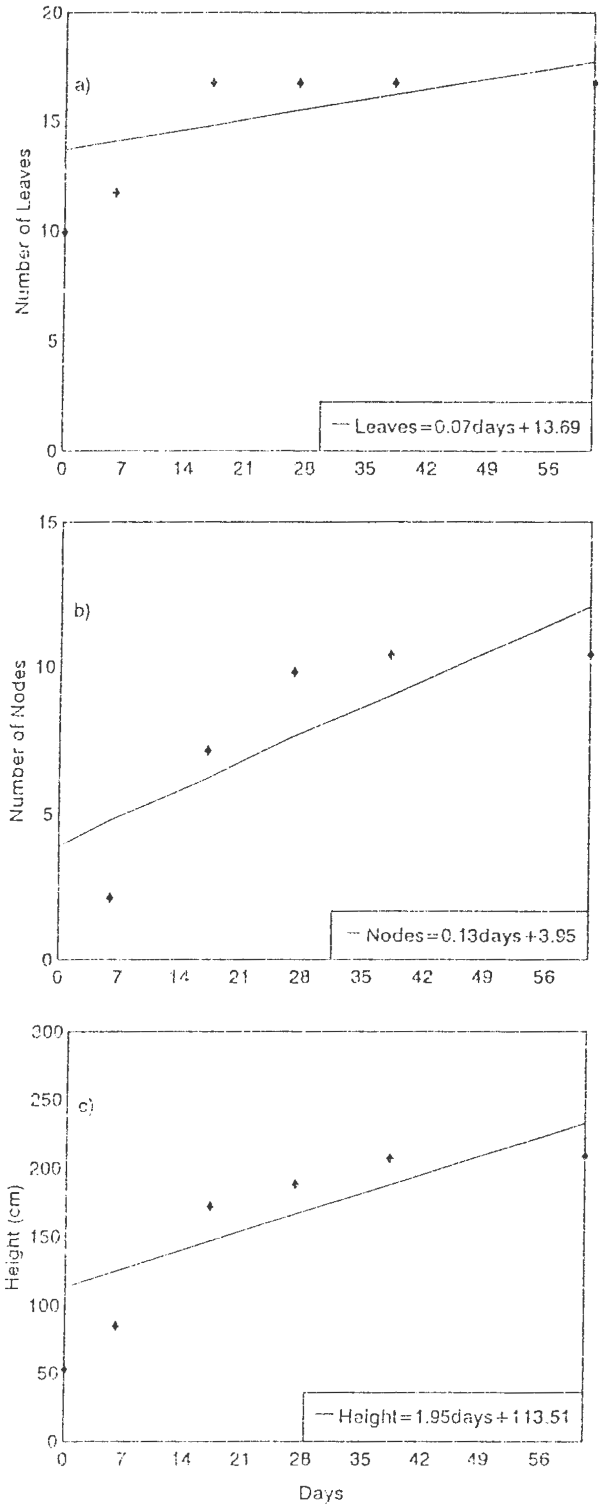


Figure 8. Linear regression of a) number of leaves on days, b) number of visible nodes on days, and c) plant height on days for cultivar Waconia grown at AAERC in 1993.

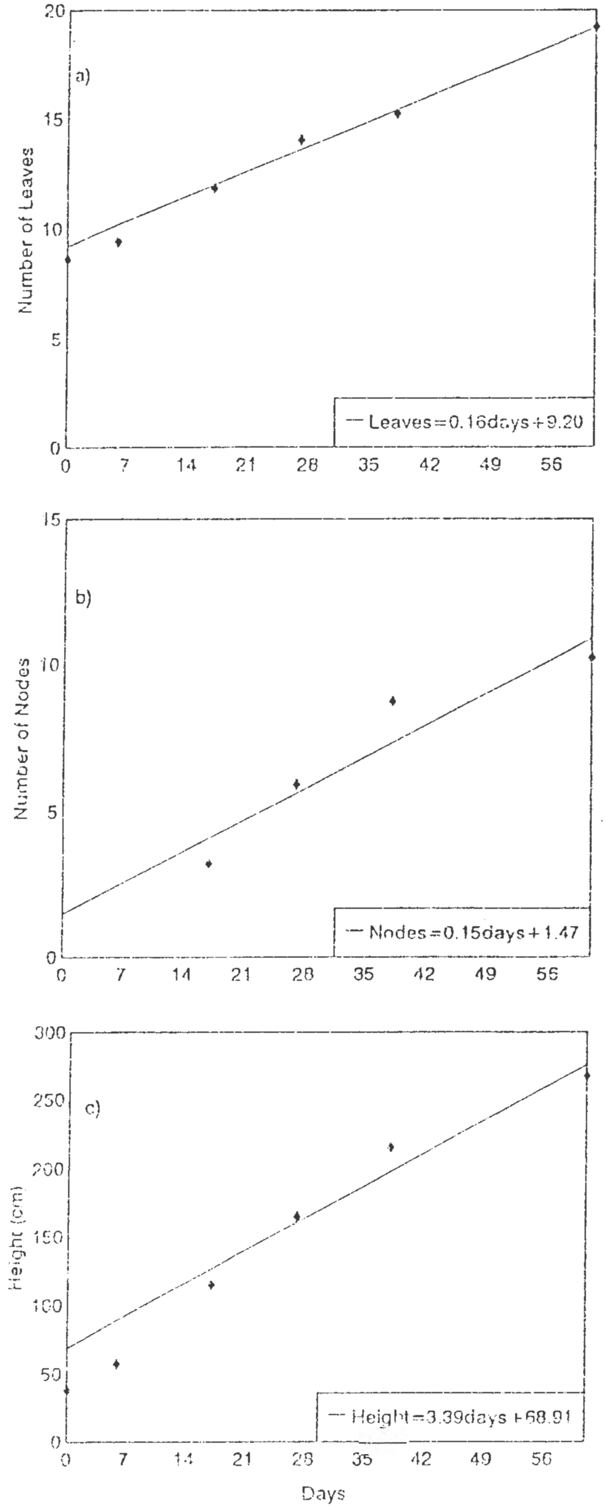


Figure 9. Linear regression of a) number of leaves on days, b) number of visible nodes on days, and c) plant height on days for cultivar Grassl grown at AAERC in 1993.

Table 31. Mean yields of lactic acid, acetic acid, ethanol, and total sugar yield for eleven cultivars ensiled in 1991-1993 at AAERC.

Year	Cultivar	Lactic acid	Acetic acid	Ethanol	Total sugar
		---------------------L ha^{-1}		---------------------	---kg ha^{-1}---
1991	Waconia	0	231	655	7
1991	Kansas O.	0	477	623	212
1991	Smith	44	544	757	451
1991	Sugar D.	108	536	1042	500
1991	Cowley	134	467	1496	184
1991	Theis	0	465	698	263
1991	M81E	0	463	700	0
1991	Dale	0	405	1135	466
1991	Keller	0	610	1530	364
1991	Wray	67	448	1356	281
1991	Grassl	137	639	2213	1021
1991	Mean	45	480	1110	341
1992	Waconia	110	588	2121	247
1992	Kansas O.	369	569	3698	493
1992	Smith	382	425	3628	0
1992	Sugar D.	417	845	4423	294
1992	Cowley	392	400	4100	1484
1992	Theis	193	515	3913	191
1992	M81E	340	707	4336	362
1992	Dale	372	571	4351	43
1992	Keller	185	614	5254	553
1992	Wray	411	646	4422	0
1992	Grassl	487	322	3735	18
1992	Mean	333	564	3998	335
1993	Waconia	551	375	1775	1620
1993	Kansas O.	539	285	2369	920
1993	Smith	441	236	2472	569
1993	Sugar D.	511	374	2711	832
1993	Cowley	620	375	2713	977
1993	Theis	536	271	2053	514
1993	M81E	589	693	2448	1047
1993	Dale	567	379	2875	625
1993	Keller	612	326	2384	530

Table 31. (continued)

Year	Cultivar	Lactic acid	Acetic acid	Ethanol	Total sugar
		--------------------L ha^{-1}--------------------			---kg ha^{-1}---
1993	Wray	547	320	2184	588
1993	Grassl	428	248	1540	1934
1993	Mean	540	353	2320	923

Table 32. Analysis of variance for lactic acid yield of cultivar silage produced at AAERC in 1991-1993.

Source	df	Mean square (x 10^{-3})
Block	1	64.4
Cultivar	10	14.3
Error a	10	15.2
Year	2	1362.8**
Year*cultivar	20	13.6
Error b	22	15.0
Corrected total	65	
Contrast:		
Waconia vs all	1	47.6

*,** indicate significance at the .05 and .01 levels respectively

Table 33. Analysis of variance for acetic acid yield of cultivar silage produced at AAERC in 1991-1993.

Source	df	Mean square (x 10^{-3})
Block	1	79.9*
Cultivar	10	35.6
Error a	10	14.5
Year	2	248.7**
Year*cultivar	20	31.3
Error b	22	23.3
Corrected total	65	
Contrast:		
Waconia vs. all	1	29.9

*,** indicate significance at the .05 and .01 levels respectively

Table 34. Analysis of variance for ethanol yield of cultivar silage produced at AAERC in 1991-1993.

Source	df	Mean square (x 10^{-3})
Block	1	389.4
Cultivar	10	1017.1*
Error a	10	260.8
Year	2	46295.7**
Year*cultivar	20	509.7
Error b	22	344.1
Corrected total	65	
Contrast:		
Waconia vs. all	1	6072.9**

*,** indicate significance at the .05 and .01 levels respectively

Table 35. Analysis of variance for sugar yield of cultivar silage produced at AAERC in 1991-1993.

Source	df	Mean square (x 10^{-3})
Block	1	1776.3**
Cultivar	10	306.7*
Error a	10	85.1
Year	2	2512.4**
Year*cultivar	20	327.6
Error b	22	315.0
Corrected total	65	
Contrast:		
Waconia vs. all	1	55.6

*,** indicate significance at the .05 and .01 levels respectively

deterioration. The same assumption could be made for the 1992 samples since the potential for ethanol production was much greater than what was realized based on sugar yields. The switch to the smaller silo volume in 1993 may have contributed to the incomplete fermentation in that year.

Cultivar differences in ethanol production and sugar residues in the silage were more difficult to clarify. Waconia clearly differed from the other cultivars in ethanol production due to its lower yield potential (Table 34). Other cultivar differences also may be implicit in sugar yield potential, as discussed previously. In the fermentation of chopped material, the conversion rates of sugar to ethanol should not be different by cultivar unless there are variations in native microbial populations, causing varying amounts of interference. As with the differences seen in years, the differences in ethanol yield by cultivar may simply reflect the inadequacies in the storage of the silage samples.

The percentages of ethanol in solution in the silage samples (data not shown) were not much lower then those obtained in other studies. In this study, the extract ranged from 3 to 5 % ethanol. Bryan et al. (1981) achieved percentages of 5.9 to 8.9. Ethanol content of fermented juice was 6 % in work by Rajvanshi et al. (1989). These can be compared to the juice sugar concentrations of 1.3 to 8.7 % recorded by Rajvanshi et al. (1989). The 1992 and 1993 ethanol yields fall within the range of values from previous sweet sorghum studies and are comparable to those for corn.

Ethanol conversion efficiencies were calculated for all cultivars in all years (Table 36). The percentages, calculated by dividing the amount of actual ethanol produced by the potential ethanol produced, ranged from 38 to 100 %. A conversion rate of 100 percent is not unusual; this value was achieved because a conservative conversion factor was used, one which assumed a 50 % conversion rate of the carbon in sugar to ethanol. This included a 33 % loss of carbon as CO_2 and 17 % for incomplete or alternate fermentation pathways, and the consumption of carbon by yeast and other microorganisms. Our yearly mean conversion efficiency rates ranged from 57 to 77 %. Considering published ethanol recovery rates of 81 percent (Bryan et al., 1981) and 89 percent (Reidenbach and Coble, 1985) from sweet sorghum juice, the values obtained in this study were respectable. Recovery rates could be greatly improved by

Table 36. Potential ethanol yields, conversion efficiency, and energy consumed and netted by production of ethanol from sweet sorghum at AAERC in 1991-1993.

Year	Cultivar	Potential ethanol	Conversion efficiency†	Ethanol consumed§	Ethanol netted
		--L ha^{-1}--	----%-----	------L ethanol ha^{-1}------	
1991	Waconia	563	100	739	-85
1991	Kansas O.	1625	38	739	-116
1991	Smith	2007	38	739	17
1991	Sugar D.	2025	52	739	303
1991	Cowley	2275	66	739	757
1991	Theis	2813	25	739	-41
1991	M81E	2169	32	739	-39
1991	Dale	1706	67	739	395
1991	Keller	2150	71	739	791
1991	Wray	2444	56	739	616
1991	Grassl	2625	84	739	1474
1991	Mean	2036	57	739	370
1992	Waconia	3563	60	517	1605
1992	Kansas O.	5919	63	517	3182
1992	Smith	6731	54	517	3112
1992	Sugar D.	7725	57	517	3906
1992	Cowley	6463	63	517	3583
1992	Theis	6250	63	517	3396
1992	M81E	6675	65	517	3820
1992	Dale	6500	67	517	3834
1992	Keller	9175	57	517	4737
1992	Wray	6900	64	517	3905
1992	Grassl	6713	56	517	3218
1992	Mean	6601	61	517	3482
1993	Waconia	2500	71	668	1107
1993	Kansas O.	2744	86	668	1702
1993	Smith	2375	100	668	1805
1993	Sugar D.	2944	92	668	2044
1993	Cowley	2781	98	668	2045
1993	Theis	3988	52	668	1386
1993	M81E	3538	69	668	1781
1993	Dale	3269	88	668	2207
1993	Keller	3138	76	668	1717

Table 36. (continued)

Year	Cultivar	Potential ethanol	Conversion efficiency†	Ethanol consumed§	Ethanol netted
		--L ha^{-1}--	----%-----	------L ethanol ha^{-1}------	
1993	Wray	3250	67	668	1516
1993	Grassl	2913	53	668	872
1993	Mean	3040	77	668	1653

† Conversion efficiency assumes a 50 % conversion factor of sugar to ethanol.

§ Energy consumed in terms of L of ethanol per hectare in the production of the crop.

decreasing the production of byproducts, using a higher conversion factor, and increasing the rates of alcoholic fermentation.

Regardless, in most cultivar silage trials liquid fuel was produced in excess of what was consumed in the production of the crop (Table 36). The negative values for ethanol netted in 1991 can be attributed to the losses that occurred in storage. Also, nitrogen application rates were highest in 1991, thus increasing the energy consumed in crop production substantially. Conversion efficiencies would have to be increased in order to compensate for the energy consumed in isolating the ethanol from the solids in the silage. This would be the most costly aspect of ethanol production from silage. If it is assumed that the energy needed for the distillation was supplied by the fibrous bagasse of the silage, then the net ethanol values are truly a measure of energy gained.

SUMMARY AND CONCLUSIONS

Sweet sorghum yields were highest in 1992 and at the Ames location, when compared over three years and at two locations. Averaged over the three years, cultivar Grassl had the highest dry matter yields. The cultivar Keller had the highest mean sucrose and total sugar yields over the three years. Comparisons of early and late cultivars accounted for much of the difference in yield potential. Differences in percent dry matter were less straight forward. Conditions which coincided with high yields seemed to be those which allowed for long periods of growth in the time between emergence and anthesis, when crop growth rates are highest. A long period of high solar radiation between anthesis and early seed formation also seemed to be an important determinant of high yields.

Cultivar Brix readings at the Ames site show differences by cultivar, date and internode. The relationship between mean Brix values and days was best described by a linear function. The regression slopes for 1991 and 1993 were similar, but the slope for 1992 was lower. There were no clear associations the onset of reproductive development (anthesis) with sugar accumulation. The pattern of sugar concentrations in the upper and lower internodes changed over time and this pattern was slightly different each year. The sink strength of an internode changed as its growth status and that of the whole plant changed. The average Brix values were highest for both internodes measured in 1992.

Cultivar production of leaves, nodes and plant height was different for all years, but only node number and plant height were different by cultivar. The plants produced the most leaves and visible nodes and were the tallest in 1992. These characteristics also coincided with the large yields of 1992. The rates of change per day for leaf number, visible number of nodes and plant height differed by year and cultivar. In general, the fuller season cultivars had greater slopes in all categories although this trend was more pronounced in 1992. Their growth was also most accurately described by a linear model.

Ethanol yields of sweet sorghum silage made over three years were acceptable. High yields corresponded loosely with the cultivars with the highest sugar yields. The conversion efficiency could be improved by decreasing the losses due to metabolic side reactions and storage conditions. The production levels were sufficient enough to account for the energy used in producing the crop. If the energy contained in the fibrous residue was utilized in the distillation process, this positive energy balance would be maintained.

Several conclusions may be drawn from the above information. Cultivar selection affects sugar yields. Late season sweet sorghum cultivars grown in the midwest show the most promise for sugar production. Dry matter production in the latest cultivars was often limited only by frost events. Optimal conditions for sugar production were those where more time was spent in each growth stage; those cultivars that fill the growing season most completely with linear growth are the best choice. This is congruent with other studies.

Late cultivars also exhibit the most constant rates of sugar production over time. Late cultivars had the most constant (and often the highest) rates of leaf, visible node, and stalk (plant height) production. These cultivars have the longest periods of carbon gain and apparently the most efficient use of resources for maximum total sugar yield. It appears to be beneficial to plant full season sweet sorghum cultivars (those adapted to the southern U.S.) for sugar production in order to take advantage of these traits. However, in years where maturation rates are depressed (i.e. cool summers), extremely late cultivars may not produce as much sugar as slightly earlier cultivars.

The amounts of ethanol produced by the methods used in this study indicate good prospects for the use of sweet sorghum as an ethanol source in the midwest. Potential ethanol yields are highest in the cultivars with greatest sugar yields. Gains can probably be made in conversion efficiencies, based on total sugar production or ethanol potential. Efficient methods of ethanol extraction from the silage will have to be developed.

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La tierra pertence al que la trabajar -Caesar Chavez-

APPENDIX A: CROP INPUTS

Table A1. Planting and harvest dates for sweet sorghum grown at AAERC, Ames, Iowa in 1991-1993.

Year	Planting	Harvest
1991	6 June	23 Sept
1992	22 May	30 Sept
1993	9 June	1 Oct

Table A2. Planting and harvest dates for sweet sorghum grown at McMRC, near Chariton, Iowa in 1991-1993.

Year	Planting	Harvest
1991	6 June	25 Sept
1992	2 June	5 Oct
1993	11 June	12 Oct

Table A3. Inputs used and rates of application at AAERC, Ames, Iowa in 1991-1993.

Year	Input	Rate
1991	N	135 kg ha^{-1}
	P	45 kg ha^{-1}
	K	135 kg ha^{-1}
	Lasso	4.7 L ha^{-1}
	Concep	18 g 10 kg^{-1} seed
1992	N	67 kg ha^{-1}
	P	45 kg ha^{-1}
	K	135 kg ha^{-1}
	Dual 8E	2.6 L ha^{-1}
	Concep	18 g 10 kg^{-1} seed
1993	N	112 kg ha^{-1}
	P	45 kg ha^{-1}
	K	135 kg ha^{-1}
	Dual 8E	2.4 L ha^{-1}
	Concep	18 g 10 kg^{-1} seed

Table A4. Inputs use and rates of application at McMRC near Chariton, Iowa in 1991-1993.

Year	Input	Rate
1991	N	112 kg ha^{-1}
	P	67 kg ha^{-1}
	K	202 kg ha^{-1}
	Dual 8E	2.6 L ha^{-1}
	Concep	18 g 10 kg^{-1} seed
1992	N	67 kg ha^{-1}
	P	67 kg ha^{-1}
	K	202 kg ha^{-1}
	Dual 8E	2.6 L ha^{-1}
	Concep	18 g 10 kg^{-1} seed
1993	N	112 kg ha^{-1}
	P	67 kg ha^{-1}
	K	202 kg ha^{-1}
	Dual 8E	2.4 L ha^{-1}
	Concep	18 g 10 kg^{-1} seed

APPENDIX B: YIELD CHARACTERISTICS

Table B1. Stand characteristics for thirteen cultivars grown at AAERC, Ames, Iowa in 1991-1993. All values are means of two replications.

Year	Cultivar	Main stalks	Tillers†	% Lodging
		---------------culms m^{-1}-----------------		
1991	Waconia	11.7	-	70.0
	Kansas Orange	14.8	-	82.5
	Smith	9.5	-	77.5
	Sugar Drip	10.7	-	47.5
	Rio	10.2	-	45.0
	Cowley	9.2	-	45.0
	Theis	7.3	-	7.5
	M81E	12.3	-	77.5
	Dale	8.2	-	65.0
	Keller	5.0	-	60.0
	Wray	6.5	-	77.5
	Grassl	8.8	-	67.5
	Mean	9.5	-	60.2
1992	Waconia	9.7	11.3	45.0
	Kansas Orange	8.2	10.2	50.0
	Smith	5.2	9.7	10.0
	Sugar Drip	7.5	8.0	70.0
	Rio	12.5	9.8	7.5
	Cowley	7.0	6.3	17.5
	Theis	7.0	11.8	55.0
	M81E	7.2	9.7	22.5
	Dale	8.3	11.8	25.0
	Keller	8.0	6.7	20.0
	Wray	6.5	9.7	10.0
	Grassl	9.8	13.8	45.0
	Mean	8.1	9.9	31.5
1993	Waconia	7.3	12.5	2.5
	Rox Orange	8.7	9.3	2.5
	Kansas Orange	8.3	10.2	2.5
	Smith	9.2	7.2	0.0
	Sugar Drip	8.2	10.5	0.0
	Cowley	5.0	7.0	0.0
	Theis	8.3	6.5	2.5
	M81E	8.3	9.2	2.5

Table B1. (continued)

Year	Cultivar	Main stalks	Tillers†	% Lodging
1993	Dale	9.2	7.3	7.5
	Keller	6.5	3.5	2.5
	Wray	6.2	4.7	7.5
	Grassl	9.2	6.5	5.0
	Mean	7.9	7.9	2.9

† Tillers were not counted at AAERC in 1991.

Table B2. Yield characteristics of Rio and Rox Orange grown at AAERC and McMRC in 1991-1993.

Year	Location	Cultivar	% Dry matter	Dry matter	Reducing sugar	Sucrose	Total sugar
				--------------------Mg ha^{-1}	--------------------		
1991	AAERC	Rio	24.2	15.9	2.4	3.6	6.2
1991	McMRC	Rio	28.8	16.8	1.5	4.6	6.3
1992	AAERC	Rio	25.7	29.0	3.8	10.9	15.3
1992	McMRC	Rio	27.2	22.2	2.2	8.4	11.0
1993	AAERC	Rox O.	21.9	11.8	2.1	1.0	3.2
1993	McMRC	Rox O.	24.2	7.6	1.3	1.2	2.5

Table B3. Ethanol potential, ethanol yield and conversion efficiency for Rio and Rox Orange grown and AAERC in 1991-1993.

Year	Cultivar	Ethanol Potential	Ethanol Yield	Conversion Efficiency
		--------------L ha^{-1}	--------------	-------%------
1991	Rio	3853.1	1834.8	47.6
1992	Rio	9534.4	5584.4	58.6
1993	Rox O.	2010.9	1815.0	90.3